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**Port Phillip Bay Nutrient Monitoring  
Proposal-  
Scientific and Technical Advice.**

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of Victoria

# **Port Phillip Bay Nutrient Monitoring Proposal – Scientific and Technical Advice**

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## Abstract

As part of the development of a nutrient management plan for Port Phillip Bay, a workshop was held in October 1998 to discuss possible approaches to monitoring over the next decade which may provide early warning of detrimental changes to Bay nutrient cycling. Specifically, the objective of the workshop was to propose programs:

*“To provide an early warning of detrimental changes to critical elements of Bay nitrogen cycling processes that indicate an increased risk of eutrophication at Bay-wide and regional scales.”*

Four programs were proposed by the workshop. These included monitoring of:

1. Denitrification efficiency;
2. Water quality;
3. Macroalgae;
4. Benthic macroinvertebrates.

In this report, the four proposals are assessed for their feasibility and cost. Indicators are identified for each program which could signal change in nitrogen cycling. In addition, four pilot studies are proposed, to clarify the direction of future monitoring techniques. These include:

1. A study of the effectiveness of laboratory incubation of sediment cores to provide nutrient flux (and denitrification efficiency) information currently gathered by benthic chambers;
2. A study of the possibility of using depth of maximum nitrate concentration in sediment cores as a surrogate for denitrification efficiency;
3. A study of the impact of exotic fauna (eg. *Sabella spallanzanii* and *Corbula gibba*) on nitrogen recycling;
4. Collection of the local data required to calibrate a new generation of satellites, to estimate chlorophyll concentration and productivity in Port Phillip Bay.

To a large extent, the ability of any of these programs to provide an early warning of possible changes in the nitrogen cycle will depend on the type, magnitude, duration and location of any possible impact. Some specific details of proposed programs, such as number and location of sites and frequency of sampling, require statistical analysis of existing data. These proposals should be seen as a step in increasing our ability to understand and manage the impact of nutrient inputs to a complex system, and in determining the effectiveness of nutrient management activities in protecting Port Phillip Bay.

This advice was prepared for Parks, Flora and Fauna Division of the Department of Natural Resources and Environment, and the Environment Protection Authority, as part of Project NP/15/0021 1.

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## INTRODUCTION

As part of the development of a nutrient management plan for Port Phillip Bay, a workshop was held in October 1998 to discuss possible approaches to monitoring over the next decade which may provide early warning of detrimental changes to Bay nutrient cycling. Workshop participants are listed in Appendix 2, and notes from the workshop appear in Appendix 3. The monitoring workshop identified and prioritised monitoring approaches and indicators in terms of the following objective: *“To provide an early warning of detrimental changes to critical elements of Bay nitrogen cycling processes that indicate an increased risk of eutrophication at Bay-wide and regional scales.”*

The workshop identified a number of possible approaches to address the objective. The purpose of this report is to build on the advice from the workshop on monitoring Bay nitrogen cycling and provide, as far as possible and predictable, the further scientific and logistical advice (including background rationale) that will be needed to:

- (a) identify whether approaches are currently feasible to pursue – particularly for “lower priorities” (for the monitoring objective in question)
- (b) identify where methods development, QA/QC programs, pilot studies are required
- (c) develop a proposed statistical design for the components that can be pursued now.

Where further work, such as pilot studies, is recommended, at least preliminary specifications/designs and costs were to be provided.

In terms of statistical design, scientific understanding about the indicators and their role in nutrient cycling is needed to:

1. guide identification of an appropriate statistical model for data analysis (eg: regression model to assess trends; t-test for comparison with a criterion)
2. design a sampling program that will provide appropriate data - this includes relevant sampling scales, sites, times based on understanding of the relevant processes
3. identify levels of, or changes in, the indicators that the program and subsequent statistical analysis need to provide acceptable confidence of detecting change.

The statistical design itself is beyond the scope of this report.

In terms of feasibility and alternative approaches, establishing cheaper surrogate measurements or indicators of denitrification efficiency was raised at the workshop and subsequently as a research priority that would facilitate effective future monitoring of this process. Assessment of options to the extent possible using existing Bay study data and, if required, recommendations on further appropriate research steps, was a further objective of this project.

The possible approaches (Table 1) identified by the workshop included:

1. Measurement of benthic nutrient fluxes, to estimate denitrification efficiency;
2. Water quality monitoring at fixed sites, including:
  - (i) continuous monitoring for some variables,
  - (ii) regular sampling for others, and
  - (iii) occasional mapping of others;
3. Mapping of benthic macroalgae;
4. Study of benthic macroinvertebrates.

**Table 1.** Approaches to nitrogen cycle monitoring recommended by workshop.

<b>Approach</b>	<b>Indicator</b>	<b>Priority</b>
Sediment fluxes	Flux of C, N, Si, P, O <sub>2</sub> between sediment and water; Rates of denitrification, decomposition & irrigation	High
Continuous water column	DO, salinity, temperature, chlorophyll fluorescence, PAR over depth	High
Regular water column	Standard suite of nutrients, chlorophyll, PAR attenuation (phytoplankton composition including toxic species if cost-effective but not critical for this objective)	High
Spatial mapping of water column	DO, salinity, temperature, chlorophyll fluorescence, standard suite of nutrients	Lower – if can be done cheaply
Benthic macroalgae	Biomass and cover	Lower – but may assist interpretation and also relevant to other management objectives
Benthic macroinvertebrates	Composition at resolution of at least functional groups, major bioirrigators and bioturbators	Lower – but may assist interpretation and also relevant to other management objectives

These approaches will be assessed in light of each of the objectives of this project.

## BACKGROUND

### *Approach to Bay nutrient management*

The Port Phillip Bay Environmental Study (PPBES) improved and synthesised scientific understanding of nutrient cycling, focusing particularly at a Bay-wide scale. This understanding was applied to smaller regions of the Bay principally through model development. Recommendations relating to a range of aspects of Bay environmental management, including nutrient management, arose from the PPBES (Harris *et al.* 1996). These recommendations included establishment of an ongoing monitoring program (Newell and Harris 1997).

The State Environment Protection Plan (SEPP) for Port Phillip Bay includes a target of a 1000 tonne reduction in annual Bay nitrogen inputs consistent with the first of the PPBES nutrient management recommendations (Harris *et al.* 1996, p 218). A Nutrient Reduction Plan (as referred to by the SEPP) outlining the approach to addressing this target is being established as part of an integrated management framework for the Bay. Several projects leading to an appropriate monitoring approach for nutrients are under development. The workshop was one step in the process and considered the Bay nutrient cycling component. The monitoring of catchment and other inputs is being considered through separate programs.

### *Current understanding of Bay nutrient cycling*

As a result of the PPBES, our current understanding of nitrogen cycling is as follows.

The main external nitrogen inputs to the Bay are the Western Treatment Plant (and a few other licensed discharges), catchment waterways, the atmosphere and, to a much smaller extent, ground water. The Bay they enter contains, at an instantaneous snapshot, large pools of nitrogen in the sediments (Nicholson *et al.* 1996, water column (Longmore *et al.* 1996) and biomass of the flora and fauna. Substantial recycling of N occurs between Bay N pools, as illustrated by the substantially higher levels of phytoplankton and microalgal productivity than expected from input loads. The finely balanced N transformations and fluxes involved in these recycling processes are tightly coupled. Coupled nitrification (conversion of ammonium to nitrate) and denitrification (conversion of nitrate to N<sub>2</sub>) and subsequent loss of N<sub>2</sub> gas to the atmosphere) is currently the dominant sink for N in the system. Overall, external N inputs to the Bay nitrogen cycling system are thought to be balanced by denitrification and, to a lesser extent, exchange with Bass Strait. It is possible, however, that N is accumulating in the sediments, developing a substantial reservoir of semi-labile organic N. This process is assumed to be negligible to Bay N cycling in the PPBES model, but is recognised as a significant remaining uncertainty (Murray and Parslow 1997).

The PPBES emphasised the links between adverse effects on nitrogen cycling processes and eutrophication risk to the Bay (Murray and Parslow 1997). From a Bay-wide perspective, the modelling predicted an almost linear response of most of these pools and fluxes to relatively small changes in N load. The response becomes highly non-linear for large loads and a breakdown in denitrification, leading to rapid transition to a highly eutrophic state, is predicted “probably somewhere in the range from 2-3 times current loadings”. There are indications that high sediment respiration rates and low denitrification efficiency already occur in Hobsons Bay (Berelson *et al.* 1998).

Although nitrogen is the critical nutrient, the PPBES also highlighted the importance of nitrogen-silicate interactions in controlling bloom biomass and composition at the regional level.

### **Why do we need to monitor Bay nutrient cycling and address key scientific uncertainties?**

- Monitoring of inputs alone has inherent limitations:
  - some input levels are currently very uncertain and/or difficult to measure accurately
  - temporal variability limits our ability to discern change particularly over short periods
  - realistically, monitoring will, at best, focus on the major inputs.
  
- Uncertainties in our understanding of Bay nitrogen cycling remain. The PPBES nutrient management recommendations focused on reducing inputs but they also identified some critical remaining scientific uncertainties about nutrient cycling processes, particularly denitrification. It remains possible that current strategies are not sufficiently conservative or overlook important additional influences on these processes.
  
- Despite input reduction strategies, unforeseen events can happen, such as spills containing nutrients or the introduction of exotic marine organisms, that affect nutrient cycling, and monitoring should provide a basis for assessing their implications to nutrient cycling.

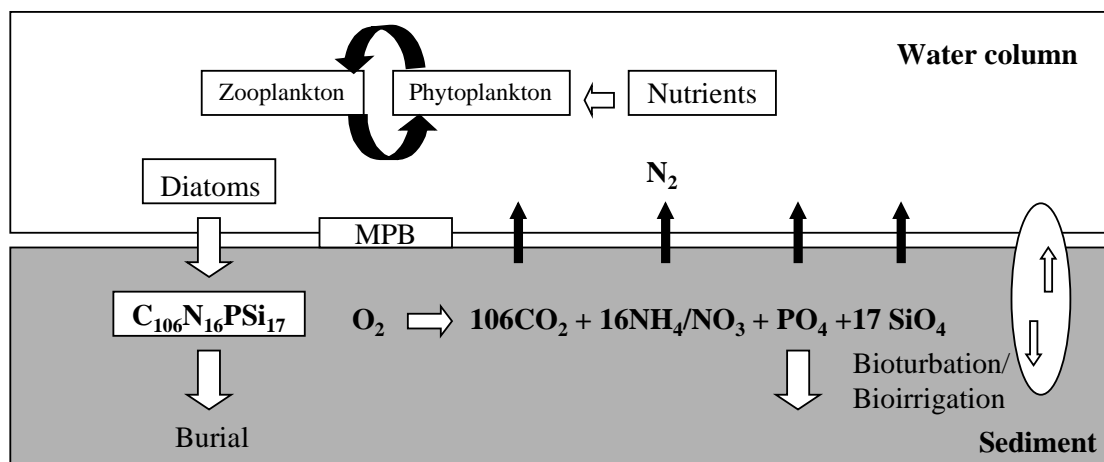
Approaches to monitoring recommended by the workshop will now be assessed. To recap, the recommended approaches were:

1. Measurement of benthic nutrient fluxes, to estimate denitrification efficiency;
2. Water quality monitoring at fixed sites, including:
  - (i) continuous monitoring for some variables,
  - (ii) regular sampling for others, and
  - (iii) occasional mapping of others;
3. Monitoring of benthic macroalgae; and
4. Monitoring of benthic macroinvertebrates

# 1. BENTHIC FLUXES

## 1.1 Rationale

The approach is based on the understanding that increased nitrogen inputs to the Bay will be rapidly transformed to phytoplankton biomass, a large proportion of which settles to the bottom (Fig 1). Bacteria on and in the sediment then begin to break down the organic matter, consuming oxygen, and returning carbon dioxide and nutrients to the water column (a nutrient flux). A close coupling of nitrifying and denitrifying bacteria within the sediment leads to the conversion of most of the recycled organic nitrogen to N<sub>2</sub> gas, which is lost to the atmosphere. Nitrifying bacteria require oxygen, whereas denitrifying bacteria cannot work in the presence of oxygen. Close coupling of the two processes requires the transport of molecules between oxygen-rich and oxygen-free zones in the sediment, and since the first step (nitrification) requires oxygen, denitrification may be limited by the availability of oxygen. Port Phillip Bay appears to be much more efficient at denitrification than most northern hemisphere marine embayments (Berelson *et al.* 1998), and maintenance of a high denitrification efficiency is critical to the maintenance of good water quality in Port Phillip Bay (Harris *et al.* 1996). Bioirrigation by infauna has been identified as an important process in nitrification and denitrification in Port Phillip Bay (Nicholson *et al.* 1996), though it is not yet clear whether this is because the bioirrigation introduces more oxygen to the sediment, or enhances the transport of molecules from nitrifying to denitrifying zones, or if burrow walls simply provide a greater surface area for bacteria to colonise. A decline in denitrification efficiency results in the return to the water column of nitrogen in forms that support algal growth. Denitrification efficiency is lower in Hobsons Bay than elsewhere in Port Phillip Bay (Nicholson *et al.* 1996; Berelson *et al.* 1998), possibly because of a higher rate of supply of organic material, and lower supply of oxygen to the sediment surface. Seitzinger and Nixon (1985) found that as experimental tanks were increasingly enriched with nutrients, the rate of denitrification increased, but efficiency decreased, so that an increasing proportion of the recycled nitrogen was returned to the water column as ammonium.



**Figure 1.** Nutrient recycling conceptual model.

Following the nutrient-processing scheme outlined above, we could theoretically detect the impact of increased nitrogen inputs as:

- increased nitrogen concentrations in the water column;
- increased plankton biomass;
- increased deposition of organic matter on the sediment;
- increased sediment oxygen consumption;
- increased nutrient flux from sediment (which feeds back to the first point).

However, pulsed nutrient inputs are difficult to monitor, since they are variable in time and space. Phytoplankton production is notoriously patchy, and also difficult to monitor at appropriate scales (though remote sensing may provide data on appropriate spatial scales in the next few years). Because of the close coupling between primary productivity and benthic fluxes, the Bay floor may act as a short-term integrator of the “rain” of production from the overlying water column, broadening in time the impact of the pulse in production. Measurement of sediment nutrient fluxes may therefore lead to an increased likelihood of successful detection of the impact of nitrogen inputs.

## **1.2 Indicators**

Indicators of impending eutrophication provided by this program include:

- Sediment denitrification efficiency,
- Sediment oxygen consumption,
- Sediment carbon dioxide production.

Another indicator of change of significance to denitrification, without necessarily being a consequence of impending eutrophication, is a change in the degree of bioirrigation brought about by changes in infauna.

## **1.3 Detecting and interpreting change**

### **1.3.1 Signal of concern**

The primary signal of concern is a decline in denitrification efficiency, and increases in oxygen and carbon fluxes. However, signs of an increase in efficiency would also be important, possibly indicating a reduction in nutrient supply to the Bay.

### **1.3.2 Scale of change**

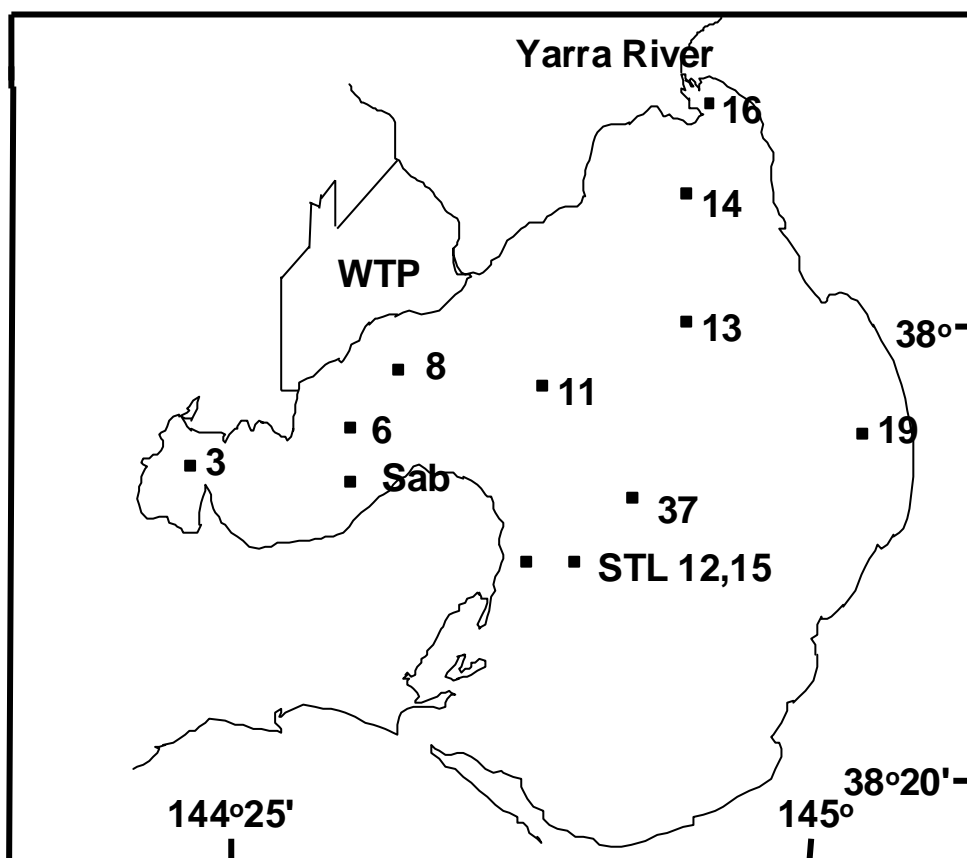
Denitrification efficiency currently varies both in time and space in Port Phillip Bay (Fig 2, Table 2). Year-to-year variation in denitrification efficiency at one site in Port Phillip Bay was less than 15% (Berelson *et al.* 1998). Seasonal variation in fluxes (not efficiency) was about 50% (summer fluxes were twice winter fluxes), relating to the seasonal change in primary production. Denitrification efficiency varied from 71-93% in most of the Bay to 28% in Hobsons Bay in summer, and the decline was reproducible between years (1994 and 1995). In both winter and summer, denitrification efficiency was always lower in Hobsons Bay than elsewhere. However, denitrification efficiency also varied significantly over a few weeks in summer in Hobsons Bay (Table 2).

Changes of denitrification efficiency in both space and time are important.

### 1.3.3 Magnitude of change

The scale of change in denitrification efficiency observed may not be great, but will vary from one area to the next. The PPBES model predicts a decline in denitrification efficiency in central PPB of only 3% for a 70% increase in current riverine loads. However, the predicted impact is greater at those sites closer to the inputs (eg. a decline in efficiency in Hobsons Bay from 48% to 35%). Based on model predictions and existing measurements, the major signal of concern (Table 2) could include a decline in denitrification efficiency below about 75% at any time in the centre, 60% off Werribee and below 60% in autumn-spring in Hobsons Bay.

**Figure 2.** Sites sampled with benthic chambers.



Change may manifest in the areal extent of low denitrification efficiency, duration of low efficiency, or a change in the absolute value of efficiency. Increasing spatial extent could be addressed by sampling multiple sites near Hobsons Bay (assuming that is where a possible nutrient increase may occur, though this assumption should be tested against predictions of population growth areas in the next decade, and the areas of monitoring changed if necessary). A change in the absolute value of efficiency will be detected by sampling at the time of predicted highest primary production. Primary production follows the temperature cycle (Neira *et al.* 1999), and benthic carbon cycling follows primary production (Nicholson *et al.* 1996). Twice yearly (summer/winter or spring/summer) sampling of benthic fluxes may be sufficient to detect long-term changes, but provision could be made for sampling at other times, or for additional surveys following some infrequent loading event. For example, the CSIRO model predicts greatest suppression of denitrification in Hobsons Bay during and following the main Yarra flood (in spring, for only one measurement has been made). Sampling may

therefore be most informative at the end of the spring flood (usually October-November, but note that high flows have occurred as late as January, so timing of sampling would have to be flexible), and some time later (eg in December), so that a change in the duration of low efficiency may be detected. Contrast this with Rysgaard *et al.* (1998), who found that changes in nitrogen cycling brought about by a pulse input may disappear within a month of the input. We are therefore unsure that brief impacts on benthic fluxes could be detected without unrealistically high sampling rates (at least twice per month). This could be verified by sampling four times over two months at one site in Hobsons Bay after a spring flood, the results of which would guide all future sampling.

Sampling should also be carried out at one or more other sites, to detect bay-wide impacts, eg. from changes to benthic invertebrate populations.

**Table 2.** Variation of denitrification efficiency with site and season.

Site	Month	Denitrification efficiency (%)
Hobsons Bay (site 16)	Jan 94	14
	Oct 94	67
	Feb 95	30
	Mar 95	49
	Aug 95	60
	Jan 96	72
Central Bay (site 37)	Oct 94	100
	Feb 95	91
	Aug 95	80
	Jan 96	78
Werribee (site 6)	Oct 94	83
	Nov 94	90
	Dec 94	89
	Jan 95	88
	Feb 95	67
	Mar 95	95
	Apr 95	77
	May 95	68
Jun 95	66	

### 1.3.4 Other variables that may explain noise.

Denitrification efficiency is apparently not related to microphytobenthic productivity but may be negatively correlated with bio-irrigation rate (Berelson *et al.* 1998). However, denitrification efficiency is driven by primary production, and measurement of primary production at about the time of benthic flux measurement may reduce some of the noise. Microphytobenthos also have the potential to modify benthic fluxes, though there was little evidence of that in most benthic chamber measurements from the PPBES (Nicholson *et al.* 1996). The PPBES integrated model predicts that the presence/absence and extent of a spring flood in the Yarra strongly affects the extent of denitrification in Hobsons Bay. An increasing biomass of macroalgae may affect denitrification efficiency, if the organic matter is harder for bacteria to break down than

planktonic cells. A dramatic change in type and/or density of infauna may also affect denitrification, by changing the depth or degree to which oxygen is pumped into the sediment. Bird *et al.* (1996) observed shrimp burrows extending at least 26 cm deep in the sediment. Radioactive tracer measurements indicated sediment mixing by infauna to about 50 cm (Hancock *et al.* 1997). Measurement of bay-wide net bio-irrigation rates is proposed (see below) to provide information on the impact of changes in infauna on benthic processes. River flow data (and some nutrient load data) will be available from the State River Monitoring Network.

### **1.3.5 Are variability estimates available at relevant scales?**

Three data sets cover a range of temporal and spatial scales in denitrification efficiency:

- Seasonal variation may be derived from a 9-month study at Werribee (Nicholson *et al.* 1996);
- Small-scale spatial (1-2 m) variability was measured at a number of sites in Nicholson *et al.* (1996);
- larger-scale (tens of metres) variability was found in Hobsons Bay (Table 2);
- short-term (2 days-6 week) variability was measured at one site (Longmore *et al.* 1996b);
- annual variability has been measured at a number of sites in Berelson *et al.* (1998).

Assuming twice-yearly sampling, early warning would not be available for at least 12 months (from comparison between seasonal values) and probably not confirmed until 3-4 years. More frequent sampling may not lead to improved early warning unless the time scale of changes in nutrient input are known (eg. is the concern one of additional loads from infrequent events from known sources, or a steady increase in an un-monitored input).

### **1.4. Confidence in interpretation/misinterpretation**

The link between primary production and benthic carbon dioxide flux is strong (Nicholson *et al.* 1996, p 96). There is little lag between change in primary production and change in carbon dioxide flux (<3 weeks). The relationship between benthic carbon flux and denitrification efficiency is strong, but also strongly dependent on a few points from Hobsons Bay (Berelson *et al.* 1998, p 927). More data are needed at moderate to high organic carbon oxidation rates for higher confidence. At this stage, the relationship is inverse linear and from the PPB integrated model we can assume that it will remain so over the range of carbon loadings likely to be found in Port Phillip Bay over the next decade.

However, much of our understanding of temporal changes in denitrification efficiency depends on the PPB integrated model, rather than direct observation. For example, as outlined above, the integrated model predicts a decline in denitrification efficiency in Hobsons Bay following the spring flood. On the other hand, Table 2 indicates a high efficiency was observed in Hobsons Bay in October 1994, at the end of the small spring flow in a dry year, while low efficiencies were observed at the same site in February and March 1995, 4-5 months after the peak flow. Also, higher efficiency was observed in Hobsons Bay in January 1996 than at the peak of the spring flow in a more typical year (in August 1995). There may be differences in behaviour between dry years and those of more “normal” river flow, and these can only be verified by direct measurement.

Denitrification can also occur in the water column, but is significant only in very turbid waters (Omnes *et al.* 1996). The particulate and nitrate concentrations in Port Phillip Bay waters are too low for this to be a significant process (though it may be important in nitrate-rich turbid plumes from the Yarra River).

## 1.5. Suggested methods and alternative approaches

Denitrification has been measured in several ways, mostly divided between *in situ* methods and laboratory incubation methods (Table 3). Some studies (eg. Nielsen and Glud 1996) have found different methods give comparable measurements, while others (eg. Ogilvie *et al.* 1997, Glud *et al.* 1998) have found significant differences between methods. Given the number of variables important in sedimentary recycling processes, it is difficult to duplicate field conditions in the laboratory well enough to confidently apply laboratory measurements to the field (Gillham *et al.* 1990). Of most concern to us in Port Phillip Bay are the findings of Kristensen *et al.* 1991, Nicholson *et al.* (1996), Gilbert *et al.* (1997) and Glud *et al.* (1998), that bio-irrigation enhances denitrification by 150-500%. Techniques (eg. collecting sediment cores) which do not adequately incorporate the impacts of infauna will lead to false estimates of denitrification (Nielsen and Glud 1998).

### 1.5.1 *In situ* (benthic chambers)

The proposal advanced in this report is to use benthic chambers to monitor indicators of the sediment denitrification process. Benthic chambers offer several advantages over laboratory incubation of sediment cores, including:

1. Benthic chambers cover a relatively large area of sediment, smoothing out the small-scale patchiness that otherwise requires collection of multiple cores;
2. Measurement takes place in a system undisturbed by handling, transport, etc, and under natural conditions of salinity, temperature and light;
3. The impact of infauna on fluxes is included;
4. The impact of benthic algae on fluxes may be assessed (with pairs of transparent and opaque chambers);
5. Attempts can be made to approximate bottom currents by careful selection of benthic chamber stirring rate.

Benthic fluxes of CO<sub>2</sub>, N (NH<sub>4</sub>, NO<sub>2</sub>, NO<sub>3</sub>), PO<sub>4</sub>, SiO<sub>4</sub> and O<sub>2</sub> will be measured at a number of key sites, and estimates made of denitrification efficiency. Benthic irrigation rates within each chamber will also be estimated by loss of an inert tracer from the chamber over time, since it has been shown that irrigation rates correlate well with enhanced nutrient fluxes (Berelson *et al.* 1998). These location-specific estimates could be enhanced by measurement of baywide average porewater exchange with <sup>224</sup>Ra (Hancock *et al.* 1997). The location and number of sites, and frequency of sampling, will be determined by statistical analysis of existing data.

Measuring denitrification efficiency with benthic chambers may be implemented immediately. There is no need to develop new technology (the up-front cost in Appendix 1 Table 4a is to build a second automated chamber to allow duplicate measurements at each site). Extensive experience has been gained in the use of this approach in Port Phillip Bay and several other water bodies over the past six years, including Moreton Bay, Qld (Heggie *et al.* 1998), Wilson Inlet, W.A. (Fredericks *et al.*

1999), Western Port (Longmore *et al.* 1998a) and Gippsland Lakes (Longmore *et al.* 1998b).

Denitrification efficiency is estimated by comparing the nitrogen (ammonium and nitrate) evolved from the sediment with that we predict from the carbon dioxide production rate, assuming the organic material being broken down is phytoplankton with a known composition (Fig 1). If the organic supply to the sediment was no longer dominated by diatomaceous plankton (eg. if macroalgae increased in importance), the current assumptions used to estimate denitrification efficiency would fail, and direct measurement of  $N_2$  would be essential. Direct measurement of  $N_2$  flux in benthic chambers is now available at a Canberra facility.

### **1.5.2 Laboratory incubations.**

An alternative way of measuring denitrification would be to carry out laboratory incubations of sediment cores (as in Table 3), by which many sites could be sampled rapidly. However, denitrification in Port Phillip Bay is tightly coupled to nitrification, which is itself closely linked to oxygen supply to the sediments (Berelson *et al.* 1997). Bioirrigation in the sediments greatly enhances oxygen supply, and any method to estimate nitrogen cycling in Port Phillip Bay sediments must allow for the impact of bioirrigators. Currie and Parry (1996) found most infauna (68%) occurred in the top 5 cm of a sediment core 20 cm deep from St Leonards. However, since some of the dominant infauna create burrows up to 50 cm deep and over a similar area (Bird *et al.* 1996), collection of sediment cores 5-20 cm in diameter will rarely capture such features. Fluxes calculated from sediment cores in these circumstances will almost certainly be greatly under-estimated. However, we do not know how important to denitrification the large, deep burrows are, compared to those of infauna that may be captured in cores 10-15 cm deep.

For these reasons, a pilot study is proposed, in which benthic fluxes (including denitrification efficiency) are estimated in areas of intense bioirrigation both from benthic chambers *in situ*, and from sediment cores collected at the same sites. Should cores and chambers produce similar estimates, all subsequent monitoring could be carried out with cores.

**Table 3.** Methods used to determine denitrification efficiency.

Method	Strengths	Weaknesses	Reference
Directly as N <sub>2</sub> production in benthic chambers	Direct measurements made of N <sub>2</sub> , NH <sub>4</sub> , NO <sub>2</sub> and NO <sub>3</sub> flux. Chambers cover relatively large area of sediment.	Need sophisticated equipment to detect small change in N <sub>2</sub> over high background. Analytical service not commercially available. Chambers relatively expensive to operate on appropriate spatial and temporal scales.	Devol <i>et al.</i> (1997)
Indirectly from nutrient fluxes in benthic chambers	Requires no sophisticated techniques. Chambers cover relatively large area of sediment.	Requires measurement of O <sub>2</sub> and CO <sub>2</sub> fluxes, and knowledge of major source of organic material. Chambers relatively expensive to operate on appropriate spatial and temporal scales.	Berelson <i>et al.</i> (1998)
Directly as N <sub>2</sub> flux in purged sediment cores	Easy to measure increase in N <sub>2</sub> concentration	Purging takes ~ 10 days to complete. Cores may not capture important infauna features of PPB.	Nowicki (1994)
Indirectly as N <sub>2</sub> O (acetylene block method)	Easy to measure increase in N <sub>2</sub> O in cores.	Acetylene also blocks nitrification, leading to under-estimates in denitrification rate. Cores may not capture important infauna features of PPB.	Ogilvie <i>et al.</i> (1997)
Indirectly as <sup>15</sup> N <sup>14</sup> N production in sediment cores (isotope pairing technique)	Denitrification measured from the accumulation of <sup>29</sup> N <sub>2</sub> and <sup>30</sup> N <sub>2</sub> following the addition of <sup>15</sup> N-NO <sub>3</sub> to the overlying water.	Unlabelled N <sub>2</sub> production not measured. Still need to measure NH <sub>4</sub> , NO <sub>2</sub> and NO <sub>3</sub> fluxes. Isotope analyses very expensive and slow to complete (months in Danish facility); not available in Australia. Cores may not capture important infauna features of PPB. Rates under-estimated in heterogeneous sediments	Nielsen <i>et al.</i> (1995); van Luijn <i>et al.</i> (1996)
Indirectly from pore water profiles	Simple to collect many sediment cores.	Expensive to section and analyse sediment cores at sufficient depth intervals to produce meaningful flux estimates. Requires knowledge of sediment porosity and sediment accumulation rate, assumes no mixing of sediment. Estimates ignore pumping by infauna.	Vanderborght <i>et al.</i> (1977); Christensen and Rowe (1984); Devol <i>et al.</i> (1997)
Indirectly from whole-system mass balances	Good for overall estimation of denitrification rate.	Requires extensive supporting data. Applies to whole system- no information on regional variation. Applies over long time spans (annual at best); no information on shorter time scales.	Smith <i>et al.</i> (1991)

### 1.5.3 Surrogate measurements of denitrification efficiency

Because measurement of benthic fluxes is not a simple process, considerable interest has been expressed in the possibility of identifying a surrogate for denitrification efficiency which is more cost efficient to obtain.

As part of the Port Phillip Bay Environmental Study, sediment cores were collected from 22 sites three times over a year. The cores were cut into several depth intervals, and pore waters were extracted and analysed for nutrient content (Nicholson *et al.* 1996). The nutrient content of sediments, and the ways in which it changes with depth, may provide information on processes occurring in the sediments (though Giblin *et al.* [1997], Ogilvie *et al.* [1997] and Nedwell and Trimmer [1996] were unable to find a consistent relationship between benthic fluxes and measures of bulk sediment properties such as oxygen penetration depth, carbon content, Eh or sulphide).

Denitrification is a process (by which nitrate is converted to N<sub>2</sub> gas) which relies on prior production in the sediment of nitrate from ammonium (nitrification). The relative amounts of ammonium and nitrate at various depths were compared to denitrification efficiency measured by benthic chamber at each of the sites in January 1994 and February 1995. No interpretable relationship could be found between denitrification efficiency and ammonium (NH<sub>4</sub>) or nitrate (NO<sub>3</sub>) concentrations at any depth interval, nor with ratios of NH<sub>4</sub>/NO<sub>3</sub>, NH<sub>4</sub>/(NH<sub>4</sub>+NO<sub>3</sub>) or NO<sub>3</sub>/(NH<sub>4</sub>+NO<sub>3</sub>). However, a relationship was found between depth of maximum NO<sub>3</sub> concentration in the sediments and denitrification efficiency for sediments collected in January 1994 (Fig 3). The relationship suggests that as the zone of maximum nitrate production shifts deeper into the sediment, the efficiency of subsequent conversion to N<sub>2</sub> declines. Though the relationship is derived from only six points, and relies heavily on one point (elimination of which reduces r<sup>2</sup> from 0.72 to 0.31), it matches conceptual models of nitrogen cycling in sediments. These models generally assume a series of layers with no bioturbation, in which molecules must travel along tortuous paths between sediment grains. For these models, the depth of the nitrate maximum is governed by:

- The depth of ammonium production (ie. depth of burial of organic matter);
- Oxygen penetration depth (in PPB dependent on bioirrigation);
- Denitrification (which removes nitrate below the nitrate maximum depth).

These models predict that as the depth of the nitrate maximum increases, the pathlength over which oxygen must travel from the surface to the site of nitrification increases. Nitrification therefore becomes less efficient with increasing depth (since more of the ammonium has a chance to escape to the overlying water), and since denitrification depends on prior nitrification, it too becomes less efficient. How important bioirrigation is in blurring this model (by introducing "short cuts" through the sediment along which both oxygen and ammonium can travel) is not clear. Nevertheless, the observations match the conceptual model, though the relationship is not nearly strong enough at present to allow reliable prediction of denitrification efficiency from depth of maximum nitrate concentration.

A much stronger relationship was found between denitrification efficiency measured in Jan-Feb 1995 and Feb-Mar 1996 and silicate concentration in the 10-15 cm depth interval for sediments collected in July 1994 (Fig 4), ie. 6-18 months before the denitrification efficiency was measured. No relationship was found between silicate concentration and denitrification efficiency measured at the same time. The relationship suggests that denitrification efficiency declines many months after the silicate stored in the sediment increases. In areas of high carbon supply (eg. Hobsons Bay) we may

expect that the supply of silicate to the sediment (from algal blooms) is greater than elsewhere in Port Phillip Bay, and also that bioturbation/bio-irrigation may be reduced because of lower oxygen concentrations at the sediment surface. Under those conditions, silicate concentrations may build up in the sediments, leading to a relationship like that found. Unfortunately Berelson *et al.* (1998) did not find a decline in bioturbation at high organic supply rates. Also, silicate concentrations in pore waters roughly double from winter to summer. If the relationship held true over some months, as the regression suggests, we would expect that denitrification efficiency would also decline significantly from winter to summer. No evidence for such behaviour was found off Werribee or in the central Bay, and differing trends were observed in Hobsons Bay over three years (Table 2).

The silicate relationship has not been reported in the scientific literature, and would need much greater experimental verification before it could be used as a surrogate for denitrification efficiency. Sediment sampling is much easier to carry out on a broad scale than benthic chamber measurements, and sediment sampling could easily be integrated into a benthic chamber program. However, the relationship can only be confirmed by carrying out sediment sampling **and** benthic flux measurements simultaneously.

Further work is recommended to prove both the nitrate and silicate relationships, and such work could easily be built into the pilot study outlined above (to save time and sampling effort). However, to be of any predictive use, the comparison would need to be carried out over several seasons, and cores sectioned at much closer intervals than has so far been the case. The pilot study would then include:

- Estimation of denitrification efficiency at a minimum of 3 sites quarterly for two years using automated chambers;
- Estimation of denitrification efficiency from incubation of sediment cores from the same sites;
- Detailed measurement of nutrient (nitrate and silicate) concentration in sediment cores from the same sites.

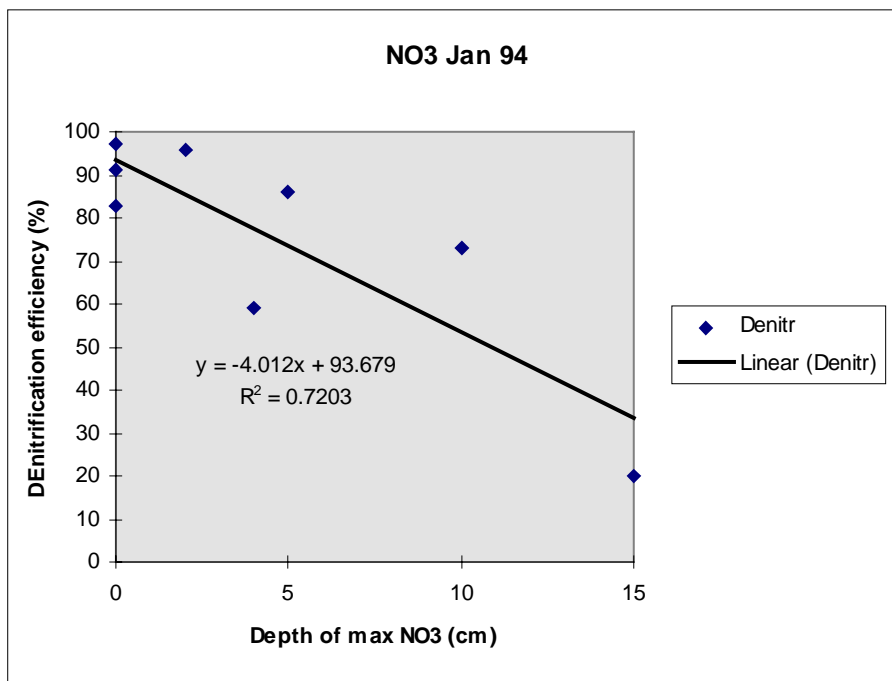
A notional cost for the pilot study is included below (Table 4c).

## **1.6 Integration with existing programs**

If benthic fluxes were measured with automated chambers, some of the fieldwork may be shared with other work proposed below. If manual sampling is chosen, vessels would be fully occupied carrying out the work, and no sharing of resources would be possible. Subject to statistical advice, sites would be selected from those chosen for water quality monitoring (Hobsons Bay, Central, Werribee). There is no evidence of low denitrification efficiency in these areas (Corio Bay and the eastern side of Port Phillip) not sampled in this scheme.

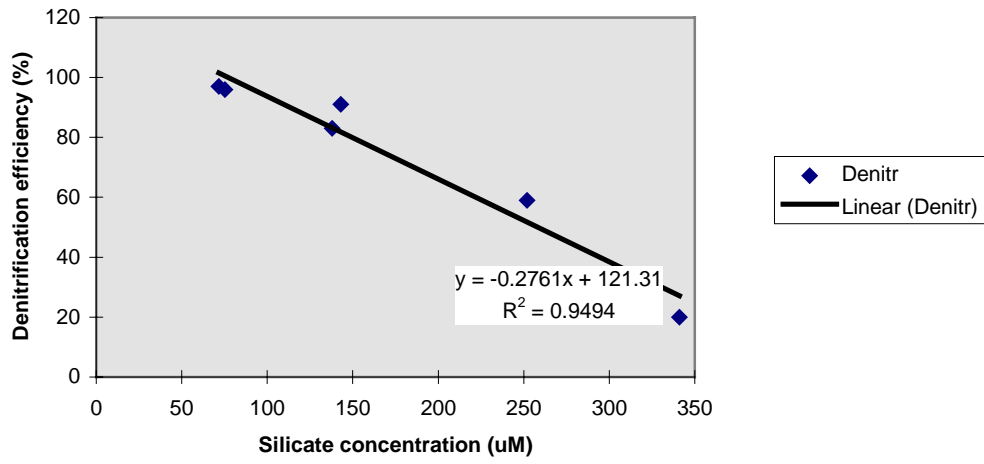
### 1.7 Recommended method

Subject to the results of a statistical analysis of existing benthic flux measurements, and also to the outcome of the pilot study outlined above, benthic fluxes should be measured at three sites (Hobsons Bay, central bay, Werribee) using a pair of transparent and opaque automated benthic chambers. Fluxes should be measured within three weeks of the time of peak phytoplankton production (determined by the bay-wide chlorophyll stock sampling proposed in the next section), and also in winter at the time of lowest phytoplankton production. Fluxes to be measured include oxygen, carbon, dioxide, ammonium, nitrite, nitrate, phosphate and silicate, with denitrification efficiency and bio-irrigation rates calculated.



**Figure 3.** Relationship between denitrification efficiency and depth of maximum nitrate concentration.

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**Figure 4.** Relationship between denitrification efficiency and silicate concentration in sediments.

## **2. WATER COLUMN MONITORING**

### **2.1 Rationale**

The approach is based on the understanding that increased nitrogen inputs to the Bay will be rapidly transformed to phytoplankton biomass, a large proportion of which settles to the bottom. Bacteria on and in the sediment then begin to break down the organic matter, consuming oxygen, and returning nutrients to the water column. This understanding is based (in part) on observations of high plankton biomass and slightly lowered oxygen concentrations in Hobsons Bay (Longmore *et al.* 1997), an area of relatively high nutrient input. High plankton biomass is also observed off the WTP, but low oxygen concentrations are not observed during the day (due to enhanced wave mixing on the open, shallow coast, and also to oxygen production by plants on the seafloor). However, there is some evidence of a decline in oxygen concentration off the WTP at night (Longmore *et al.* 1996b).

The area of the Bay in which change would be most easily detected (the centre) is also the area least likely to be impacted in the next decade by nutrient discharges. The near-shore area, with highest spatial and temporal variability, is the area most likely to be further impacted. The approach below is designed to address the problem of detecting change near-shore against a “noisy” background, where the scales of change may be days, and hundreds of metres. Comparative measurements in the Bay centre are proposed to confirm our expectations (and also because dissolved oxygen depression has been observed there in the past (Mickelson 1990)).

### **2.2 Indicators**

The indicators to be monitored in this approach include:

- nitrogen concentrations in the water column;
- plankton biomass;
- oxygen concentration in the water column;
- water column stratification (since it affects oxygen supply to the sediment).

### **2.3 How we detect and interpret change**

#### **2.3.1 Signal of concern**

Various signals may be expected to indicate declining water quality. These include:

- a decrease in bottom dissolved oxygen concentration (as increasing nutrient inputs lead to increased deposit of organic matter, and increased oxygen consumption);
- an increase in standing stock of primary producers (estimated by chlorophyll concentration);
- an increase in ambient nutrient concentration, either from the input or from increased benthic fluxes.

The PPBES integrated model predicts that an increase in nutrient discharge to Hobsons Bay would lead to increasing bloom duration, increasing duration of oxygen depletion, and an increase in bloom intensity along the eastern shore of Port Phillip Bay.

#### **2.3.2 Scale of change**

All of these signals may occur over short time frames (eg. a few days) rather than as a steady long-term increase, and such short-term responses may be missed by regular (typically monthly) sampling programs (Longmore *et al.* 1996b). Therefore continuous monitoring would be necessary if these changes are to be reliably detected. Variables such as salinity and temperature, as well as controlling the growth of some plankton, control stratification, which prevents the resupply of oxygen from the atmosphere to the water column. However, there are also other variables (eg. nutrient concentration) which are important indicators of nitrogen cycling, but which cannot yet be measured continuously. Manual sampling is required for such variables.

Mapping is the only way (other than remote sensing of colour and temperature) to measure the extent of specific discharge plumes, and also to calculate the pool size of nutrients within the Bay.

### **2.3.3 Magnitude of change**

There is little current understanding of the magnitude of changes in indicators that would indicate incipient eutrophication, but they could be quite small. For example, average dissolved oxygen (DO) concentration in Hobsons Bay is only 2-3% below that of central PPB.

The SEPP identifies levels of DO and chlorophyll for various segments of the Bay. These could readily be adopted, viz:

- DO one metre from the seafloor to be greater than 90% saturation at all sites; and
- Annual median and maximum chlorophyll *a* concentrations not to exceed levels identified for the segment of interest.

No such limits are available for nutrients, but statistical analysis of existing data could identify current conditions, beyond which no statistically significant increase would be acceptable. Alternatively, detection of a consistent trend may be used to indicate unacceptable change.

### **2.3.4 Other variables that may explain noise.**

Rainfall and river flow records are readily available. Atmospheric inputs are not well understood, and this may lead to unexplained “noise”.

### **2.3.5 Are variability estimates available at relevant scales?**

Extensive data sets are available detailing temporal and spatial variability of all variables for which sampling is proposed. These include:

- salinity and temperature continuous records for over 9 years from southern PPB (Longmore *et al.* 1998b);
- salinity, temperature and DO continuous records from central PPB over 15 months (Mickelson 1990);
- some months of continuous PAR data from a range of sites (Beardall and Light 1997);

- some months of continuous fluorescence data from a number of sites (Beardall and Light 1997);
- seven years of fortnightly fixed site samples (nutrients, physical) from 6 sites (Longmore *et al.* 1997);
- 15 years of 1-3 monthly sampling (nutrients, physical) from three fixed sites (EPA).

EPA has a draft report in preparation on trends in the EPA data. An extensive data set exists of spatial scales of change throughout the Bay determined over a two-year period by mapping (Longmore *et al.* 1996b). An analysis of variance of these data has already been carried out as part of the PPBES. This showed weak spatial gradients in the centre of the Bay (containing about 80% of the Bay volume), with significant seasonal and interannual variation for some indicators. Variability in the area from the Sands to the Rip is dominated by tidal mixing. The western side of the Bay is dominated by a seasonal (ammonium) signal from the Western Treatment Plant, while the northern part of the Bay experiences strong spatial patchiness, and strong temporal variability as a result of Yarra River runoff. Corio Bay and the Geelong Arm are influenced by the WTP discharge.

#### **2.4 Confidence of interpretation/misinterpretation in terms of an early warning**

As mentioned above, the indication of incipient eutrophication is likely to be an increase in the number or severity of specific events in the water column, rather than a general slow decline in Bay water quality. Short-term freshwater inputs may be detected by measurement of salinity to a high precision and accuracy. Continuous measurement of both DO and fluorescence will also identify short-term (hours-days) impacts of blooms, as well as detect longer-term (weeks-months) changes. Dissolved oxygen is easily measured to a suitable accuracy and precision, and in conjunction with other continuous measurements (salinity, temperature) it should be possible to distinguish between a decline in DO caused by oxygen consumption at the site and a decline caused by low-DO water moving in from elsewhere. Fluorescence response varies with phytoplankton species and nutritional health, so that changes in fluorescence may not necessarily indicate minor changes in plankton biomass. However, continuous measurement should detect major changes in biomass.

Statistical theory suggests that reliable detection of a cyclic change can only occur if sampling occurs at least twice as frequently as the duration of the event (Chatfield 1989). For example, if an event lasts for a month, it could only be reliably detected by sampling at fortnightly (or more frequent) intervals. Nutrient concentrations in the water column may increase due to discharges, or indirectly due to changes in nutrient recycling from the sediment. If it is assumed that increased nutrient inputs in the future are due to episodic events (eg. storm water), then it is probable that regular (monthly) fixed site monitoring will not detect such inputs directly (due to low frequency of sampling). To the extent that short-term (days-week) changes may not be detected, fixed site sampling may not deliver much of an early warning. However, longer-term trends may be detected.

## 2.5 Suggested method and alternative methods

This approach includes a mix of:

- continuous monitoring of some variables at several sites;
- regular sampling of fixed sites for other variables, and
- occasional mapping of a few variables over defined areas of the Bay.

The first two items were accorded a high priority by the workshop participants, and the third a lower priority.

In this proposal, instruments are deployed at a number of fixed sites, to continually measure salinity, temperature, dissolved oxygen (DO), photosynthetically active radiation (PAR) and chlorophyll fluorescence at near-surface and near-bottom depths. Measurements of salinity, temperature and DO at two or more depths are necessary to identify periods of stratification in the water column. These variables, and also a range of nutrients (which may include, subject to statistical analysis of the variability of existing data, ammonium, nitrite, nitrate, phosphate, silicate, particulate C,N,P, organic C,N,P, chlorophyll) would also be measured from a number of fixed sites at regular intervals. The variables capable of being mapped include ammonium, nitrite, nitrate, phosphate, silicate, salinity, temperature, DO and chlorophyll. While nitrogen is the prime concern, the other variables all add information about how nutrients are assimilated and recycled in the Bay.

Sites should be chosen (based on an understanding of spatial variability from statistical analysis of existing data) to identify changes in specific areas of the Bay. The continuous monitoring equipment will identify temporal scales (from hours to years) of change at each of the sites for several variables. Manual sampling of fixed sites will provide information on temporal scales from months to years. In both cases, comparisons between sites may provide information on Bay-wide changes.

Mapping is the best approach to defining the spatial scale of change over distances of kilometres, and over time-spans of days. It may either be used to intensively study special events (eg. a Yarra flood), or linked to the fixed site sampling program to provide regular images of water quality across the Bay surface.

The continuous monitoring arrays are commercial products, requiring no further development. Extensive experience in operating such equipment exists at MAFRI, with an S,T logger operating continuously for 9 years (Longmore *et al.* 1997), and others (S,T,DO, PAR) for more than 1 year (Longmore *et al.* 1998b). Fluorescence and PAR were logged continuously for some months during the PPBES (Beardall and Light 1997).

MAFRI and the EPA have carried out sampling of fixed sites for all of the variables of interest for many years; the EPA fixed site network has now collected nutrient and chlorophyll samples at three sites for over 15 years.

Mapping has been carried out in a number of environments by MAFRI over the past six years. The equipment has recently been successfully deployed in a small, fast boat (the EPA “Koorong”; Longmore *et al.* 1999). Full coverage of the Bay surface should be possible in one day.

In the longer term, chlorophyll distribution may be assessed from satellite images, but such techniques are awaiting the launch of suitable satellites and development of algorithms suitable for coastal waters. Because satellite images offer the twin potential benefits of full and detailed coverage of the Bay surface, and frequent passes from which short-term changes in biomass may be estimated (eg. 2000 1 km<sup>2</sup> pixels and approx 2 days for the SeaWiFS satellite), a pilot study is proposed, during which data suitable for ground-truthing of satellite images will be collected, to allow algorithms specific to Port Phillip Bay to be derived.

Continuous nutrient analysers are also beginning to appear on the market. While they would be an excellent addition to the continuous monitoring arrays to detect short-term changes, their current cost (approx. \$35,000 per nutrient) and limited range (nitrate, phosphate, silicate only currently available) make them an expensive addition. In time, if costs fall, they may be worth re-considering.

## **2.6. Integration with existing programs**

Servicing of monitoring arrays could be integrated with chamber deployment (a proposal rather than an existing program). It would not be possible to integrate with the EPA fixed site program in a way which would lead to reduced costs, since a full day would be needed to service the arrays. However, the fixed site sampling could readily integrate with the EPA program. Little extra effort is needed at each site beyond that already made by EPA. Subject to a review of the analysis of spatial variability mentioned above, all of the sites could coincide with those currently sampled by EPA.

The monitoring arrays should be located at fixed sites (eg. in Hobsons Bay, central PPB, Werribee), to maximise the amount of concurrent information gathered. They should also coincide with sites at which denitrification efficiency is measured.

## **2.7 Recommended method**

Subject to the results of statistical analysis of existing data, vertical profiles of salinity, temperature, dissolved oxygen, chlorophyll fluorescence and PAR should be collected twice daily from three sites (Hobsons Bay, central Bay, Werribee) using programmable buoyancy sensors.

The current EPA fixed site sampling program should be supplemented to include vertical profiling of the above variables at each site once per month. Underway analysis of salinity, temperature, chlorophyll fluorescence and nutrient (ammonium, nitrite, nitrate, phosphate, silicate) should be carried out monthly during the EPA fixed site sampling program to give a bay-wide snapshot of water quality. The timing of the EPA sampling could be varied to allow the impact on water quality of special events (eg. a large Yarra flood) to be mapped.

A pilot study should be carried out of the effectiveness of satellite monitoring of chlorophyll biomass and productivity.

### **3. BENTHIC MACROALGAE**

#### **3.1 Rationale**

Increased nutrient loads may stimulate the growth of both planktonic and macroalgal plants. Benthic plants grow along the shores of Port Phillip Bay at depths up to 10 m, and account for a significant proportion of the annual primary production in Port Phillip Bay. They produce considerable volumes of wrack, particularly after storms, which the public sees as nuisance weed on the beaches. Macroalgae growing along the western shores is mostly drift weed (unattached), while that growing down the eastern coast is attached to other substrates (mostly *Pyura*). An increase in macroalgal production could be signalled by an increase in cover, or an increase in density/biomass. The unattached macroalgae on the western side occur in patches 10-100 m in size, while patches 1 m across and 2-3 m apart occur on the eastern side. The biomass is much higher on the western side than the eastern side. Lack of light is likely to be the factor limiting growth in deeper water, while wave action prevents growth near-shore on the eastern side.

75-97% of the biomass of macroalgae occurs along the western coast (Chidgey and Edmunds 1997), and the tissue nitrogen content of 200-1000 tonnes is large enough in proportion to the annual nitrogen input to be a relevant management consideration. The PPBES integrated model predicts that decreasing WTP loads will lead to a reduction in macroalgae (Murray and Parslow 1998). It may therefore be expected that the cover and/or biomass on the western coast will decline. Similarly, cover and/or biomass on the eastern coast should decrease with decreasing catchment loads from drains and minor creeks.

Seagrasses are not considered because the only extensive beds occur in Corio Bay, the Geelong Arm and Swan Bay, all remote from existing major sources, and remote from areas where changes in land use may lead to localised increases in nitrogen loading.

#### **3.2 Indicators**

The indicator used to identify change in trophic status is an increase/decrease in biomass or cover of macroalgae.

#### **3.3 How we detect and interpret change**

##### **3.3.1 Signal of concern**

Evidence of eutrophication would be an increase in biomass, whether from increased cover or increased density, of key species or macroalgae as a whole. While it is clear that seasonal changes in biomass are large (Chidgey and Edmunds 1997), there is (so far) no evidence to show that such changes are reproducible from year to year.

##### **3.3.2 Scale of change**

This approach applies to the northern third of the bay near-shore, but especially from Little River to Altona. This area was covered by Chidgey and Edmunds (1997), and there are no strong reasons not to use those sites. Note that the spatial extent of macroalgal beds is uncertain (and probably variable).

### **3.3.3 Magnitude of change**

There is no key value above which we should be concerned; longer-term trends would provide the best evidence of change.

### **3.3.4 Other variables which may explain noise**

In a general sense, nutrient enrichment often leads to an increase in ephemeral macroalgae at the expense of perennial species (Nielsen and Jernakoff 1996). While it is true that the macroalgae off the Werribee coast is dominated by ephemeral species, substrate suitability, light attenuation, water depth, exposure to wind and sediment load may be as important in structuring macroalgal communities as nutrient availability (Light and Woelkerling 1992). Given the sensitivity of macroalgae to light, and the competition between macroalgae and phytoplankton for the same nutrient resources, change could not be unequivocally assigned to nutrient inputs, unless the other factors were first eliminated.

### **3.3.5 Are variability estimates available on appropriate scales?**

Some estimates of variability are available from the PPBES (Chidgey and Edmunds 1997), but over a period of less than two years. Samples (10 quadrats for biomass and 300 points for cover) were collected from four depths at five sites, four times over 10 months.

## **3.4 Confidence of interpretation/ misinterpretation in terms of an early warning**

Monitoring of macroalgae was assigned a lower priority by the Workshop than those approaches listed above. In part, this was because the variability in biomass (3-8 fold variation over a year at most sites) is likely to make detection of trends difficult, unless the variation can be shown to be highly reproducible from year to year. Maximum biomass occurs in spring-autumn, but varies between species (Brown *et al.* 1980). Quarterly surveys are proposed for three years, to determine if the pattern of change in biomass is repeatable from year to year. The need for further work should be assessed at that time. On present knowledge, monitoring of macroalgal biomass can not be viewed as an early warning (though with a turnover of ~3 months, it should be possible for macroalgae to respond quickly to major change).

## **3.5 Suggested method and alternative methods**

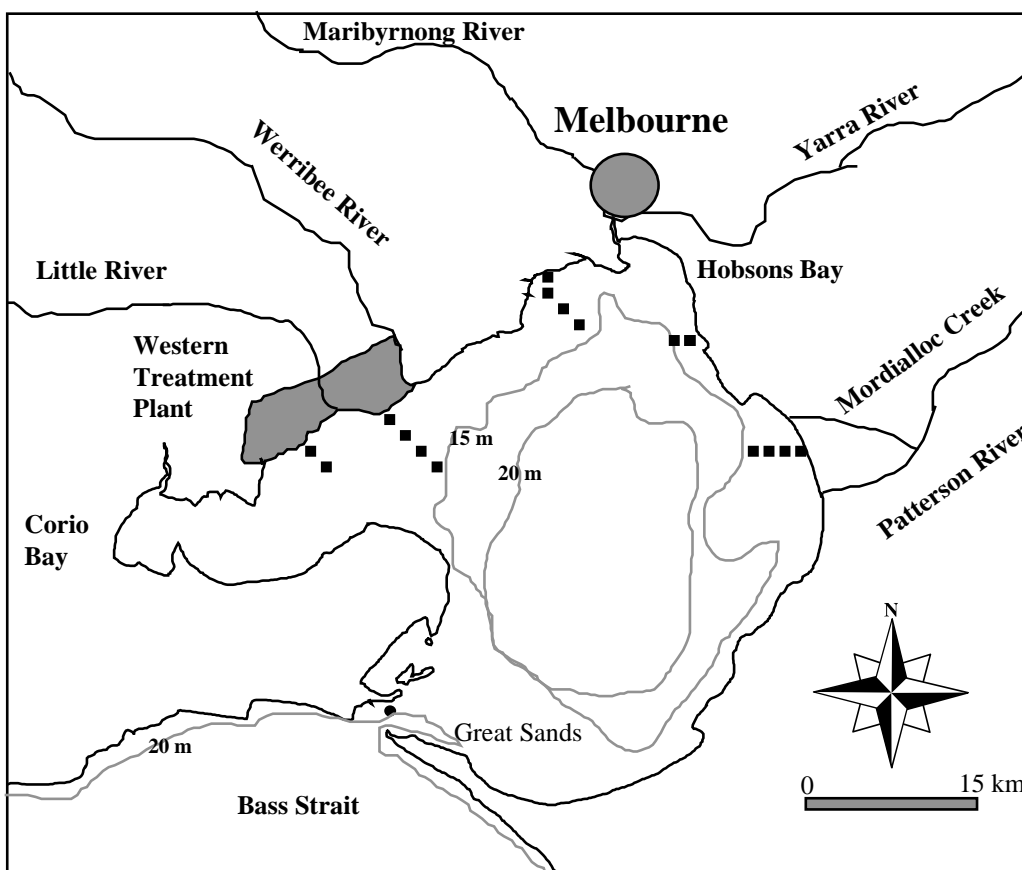
This approach consists of quarterly surveys of the cover and biomass of macroalgae at five fixed sites along the western and eastern coasts between Werribee and Frankston (Fig 5). The program described can be carried out without further development. However, it should be viewed as a developmental process, providing information on variability in biomass with site, depth and season, which will be necessary to reliably detect change.

Biomass is estimated from representative samples, and extrapolated on the basis of the video cover. This cannot be done with remote sensing, because on the western side of the Bay the relationship between cover and biomass is strongly hyperbolic; at high cover, large changes in biomass may occur for minimal changes in cover. The relationship varies greatly between sites, depths and time (Chidgey and Edmunds 1997).

Further study is needed of the biomass/cover relationship, and of the other factors listed above that may contribute to the control of macroalgal biomass or distribution. Nutrient content of macroalgae was listed as a possible monitoring tool by Nielsen and Jernakoff (1996), but Chidgey and Edmunds (1997) found the highest nitrogen content at Brighton rather than off the WTP. Conversely, there were also substantial changes in nutrient content in all major macroalgal groups between surveys, which follow the seasonal variation in WTP discharge quite closely. Whether these changes could ever be measured with sufficient precision to be useful as an early warning can only be answered by further experimental work.

### 3.6 Integration with existing programs

The characteristics of a work program involving benthic macroalgae do not lead to cost efficiencies for other proposed or existing programs.



**Figure 5.** Macroalgal sampling sites (from Chidgey and Edmunds 1997).

### 3.7 Recommended method

Quarterly surveys should be carried out of the cover and biomass of macroalgae at five fixed sites along the western and eastern coasts between Werribee and Frankston. Four depths per site should be sampled. At each depth, a 100 m video transect should be carried out along the isobath, along which 10 quadrats should be sampled for biomass

and cover. Biomass is estimated from representative samples, and extrapolated on the basis of the video cover.

## 4. BENTHIC MACROINVERTEBRATES

### 4.1 Rationale

Macrofauna (animals living on or in the sediments) have often been studied to determine the impact of pollutants on marine ecosystems, and the changes near effluent outfalls have been well described. Macrofauna play a critical role in nutrient processing in sediments (Wilson *et al.* 1993). Burrowing organisms (deposit feeders) may redistribute organic matter from the surface to deeper within the sediment, pump oxygenated water into the sediment, provide substrate for enhanced bacterial activity, and thereby promote nitrification and denitrification. Suspension feeders typically filter food from the water column, before it reaches the sediment, and may return nutrients directly to the water column.

Over the period 1969-95, there was an increase in relative number of suspension feeders in Port Phillip Bay from 23% to 33% and a decline in relative number of deposit feeders from 71% to 55% (Wilson *et al.* 1996). Suspension feeders rarely establish extensive burrow systems, in contrast to deposit feeders. It may therefore be assumed that there has been a decline in burrow volume, and a decline in microbial communities which colonise burrows and which are important in nitrification/denitrification (Bird *et al.* 1996). Denitrification efficiency may well have been higher in 1969 than it is at present.

Changes in relative abundance of groups of native fauna may be natural to some degree, but the introduction of exotic species such as *Sabella spallanzanii* is a matter of concern. Their growth habit allows them to trap organic matter in the water column, before it falls to the sediment, therefore depriving infauna of food. *Sabella* have also been shown to produce high concentrations of nitrate and ammonium (Longmore *et al.* 1996a), bypassing the normal sedimentary denitrification cycle. *Corbula gibba*, another exotic mollusc, is also a suspension feeder. Studies are currently being carried out into some aspects of its feeding ecology (Sonia Talman, Melbourne University). *Asterias* (Northern Pacific Seastar), a more recent exotic introduction, may also impact on nitrogen cycling by predation of near-surface fauna that may be important in bio-irrigation.

### 4.2 Indicators

The indicator used to identify change of significance to nitrogen cycling is the number and/or biomass of suspension feeding and deposit-feeding benthic invertebrates.

### 4.3 How we detect and interpret change

#### 4.3.1 Signal of concern

A decline in the absolute number or biomass of deposit-feeders (bioturbators/ bio-irrigators) would be a signal for concern. The principal deposit feeders identified during the PPBES include *Lumbrineris* sp. MoV322, *Leitscoloplos bifurcatus*, *Echinocardium cordatum*, *Neocallichirus limosus*, *Euchone* sp. MoV1755 and *Neocallichirus limosus* (Wilson *et al.* 1996). However, all species sampled should be identified.

#### 4.3.2 Scale of change

Interannual change in infauna populations exceeds seasonal change (Wilson *et al* 1996). Significant change occurred over 1975-1991 in some species. These changes varied spatially (eg. a decline in total numbers occurred in western sands, while an increase was observed in eastern sands, and little change in total number of species occurred in central muds). However, the major difference in populations occurred between sandy and muddy substrates. None of the samples collected in the 1990s have come from Hobsons Bay, and it is not clear what effort would be needed to detect change within Hobsons Bay itself.

#### **4.3.3 Magnitude of change**

The magnitude of change in infauna that is significant in terms of nitrogen cycling is currently unknown. While it could be crudely estimated from literature values of infaunal metabolism and estimates in changes of biomass in Port Phillip Bay (Wilson *et al.* 1993), experimental measurement of the impact is the only way of providing statistically robust estimates of the interaction of infauna on nitrogen cycling.

#### **4.3.4 Other variables which may explain noise**

Infauna are affected by many factors other than nutrient supply (eg. predation, competition for food, introduction of exotic species). The concern at present is more one of how a change in infauna may affect nutrient cycling, rather than how nutrient inputs may affect infauna.

#### **4.3.5 Are variability estimates available at appropriate scales?**

Four major macrobenthic studies have been carried out in Port Phillip Bay, in 1969-73, 1973-75, 1991-92 and 1994-95, providing 100, 180, 74 and 168 grab samples respectively from a range of sediment types. Extensive statistical analysis of the studies individually and together has been carried out (Wilson *et al.* 1996), indicating variability over short (9 month) and longer (3-20 years) times. Power analysis has been used by Wilson *et al.* (1996) to determine the number of samples needed to detect change within large areas of the Bay.

#### **4.4 Confidence of interpretation/ misinterpretation in terms of an early warning**

A decline in the absolute number of bioturbators/ bio-irrigators would be a signal for concern. We could not be confident that the decline would be due to nutrient input, but concern would be expressed because of the assumed importance of bioturbation to benthic fluxes. Note, however, that Berelson *et al.* (1998) found little relationship between irrigation and denitrification efficiency.

Similarly, detection of an increase in number of exotic species, particularly filter-feeders, may have implications for denitrification efficiency, but that would need to be established experimentally for each species of concern. Exotic predators on infauna, such as *Asterias* (the Northern Pacific Seastar), may also potentially affect denitrification, especially if near-surface infauna (more prone to predation from the surface) are more important to denitrification than deeper-living species.

Since surveys are proposed on an annual basis, there is little likelihood of this approach detecting the impact of transient inputs. A warning could only be provided on the basis of several years (at least three) of data.

#### **4.5 Suggested method and alternative methods**

This approach involves the identification to species level of macrobenthos sampled by benthic grab from the 22 sites surveyed annually since 1990 by MAFRI for fish species (Fig 6). These sites are depth-stratified along transects from Hobsons Bay, WTP, Corio Bay, Beaumaris, Mornington and St Leonards (Parry *et al.* 1995), and include the three major sediment types identified by Wilson *et al.* (1996). An advantage of sampling these sites is that much more information (the relationships between infauna and fish) is provided with no extra effort.

The proposed work is essentially a repeat of studies carried out over the past 20 years by the Museum of Victoria and MAFRI. It does not involve any new technology. Access to existing data sets would be essential in detecting change.

Grab sampling (as proposed here) is not an effective way of sampling *Sabella* (Wilson *et al.* 1996). However, epibenthic surveys at the 22 sites noted above have identified *Sabella* biomass and distribution. In addition, MAFRI will trial a dredging technique in early 2000 that is expected to reliably sample both epifauna and infauna (G. Parry, pers. comm.). If successful, this technique should be adopted for future sampling.

A pilot study is also recommended to improve our understanding of the impact of exotic species on denitrification. This would involve the measurement of changes in denitrification efficiency over a range of exotic infaunal densities. A pilot study would involve either laboratory incubation of sediments with a range of exotic bioturbators, with denitrification efficiency calculated from direct measurement of N<sub>2</sub> and dissolved inorganic nitrogen, or it could be measured in the field with benthic chambers. In the laboratory approach, it is easy to manipulate species and number of individuals, but there would be uncertainty about whether sediment structure is reproduced effectively, and whether the supply of organic matter to the sediment surface adequately represents reality. In field studies, sediment structure is maintained, but it is harder to manipulate exotic numbers. On balance, the ability to manipulate exotic numbers in the lab in a replicated way probably outweighs possible changes in sediment structure. Given enough lead-in time, tanks could be established that allow replicated measurement of the changes caused by exotic infauna.

#### **4.6 Integration with existing programs**

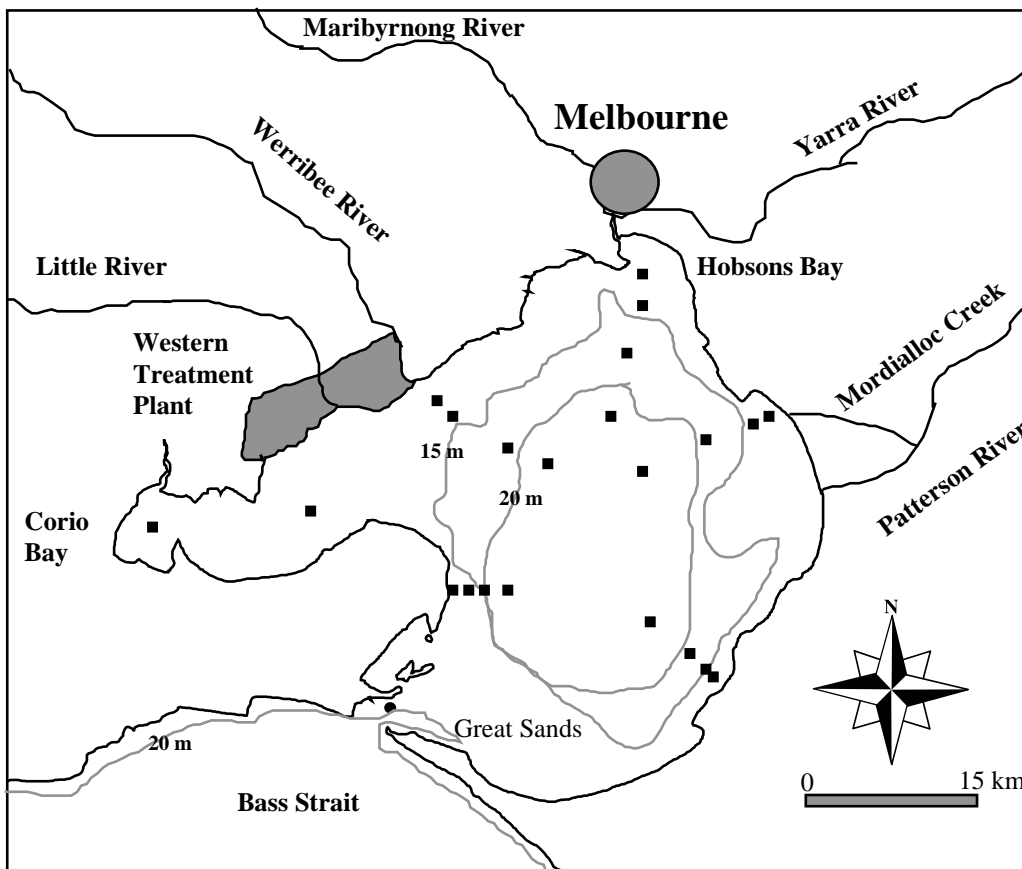
As outlined above, sampling sites should coincide with those currently sampled for epifauna and fish species. Some of these sites could also be used for benthic flux and water column measurements, but at least one extra site would be necessary in Hobsons Bay.

#### 4.7 Recommended method

Annual sampling of infauna and epifauna with a benthic grab or modified dredge is proposed at 22 sites throughout the bay. All macrobenthos collected will be identified to species level.

A pilot study is proposed, in which a range of exotic infauna will be established in laboratory tanks. Following a period sufficient to allow representative sediment structure to be established, the impact of varying exotic species and biomass on sediment denitrification efficiency will be measured.

Though monitoring of macroinvertebrates was assigned a lower priority than sediment or water column monitoring tasks by the workshop, given the changes in invertebrate populations observed since 1969, the increasing importance of exotic organisms in the bay, and the potential for changes in invertebrate populations to alter denitrification, this pilot study deserves a high priority.



**Figure 6.** Proposed sites for macrofaunal sampling (from Parry et al. 1995)

## CONCLUSIONS

Following a review of the proceedings of a workshop on monitoring nitrogen cycling in Port Phillip Bay, the following four programs are recommended.

**1. Monitoring of benthic denitrification efficiency.** Subject to the results of a statistical analysis of existing benthic flux measurements, and also to the outcome of the pilot study outlined above, benthic fluxes should be measured at three sites (Hobsons Bay, central bay, Werribee) using a pair of transparent and opaque automated benthic chambers. Fluxes should be measured within three weeks of the time of peak phytoplankton production (determined by the bay-wide chlorophyll stock sampling proposed in the next section), and also in winter at the time of lowest phytoplankton production. Fluxes to be measured include oxygen, carbon, dioxide, ammonium, nitrite, nitrate, phosphate and silicate, with denitrification efficiency and bio-irrigation rates calculated.

A pilot study is proposed, to determine if cheaper surrogates for measuring denitrification efficiency can be found, and also to determine if denitrification efficiency as measured *in situ* by benthic chambers can be replicated by laboratory incubation of sediment cores.

**2. Monitoring water column stability, and nutrient and chlorophyll stocks.** Subject to the results of statistical analysis of existing data, vertical profiles of salinity, temperature, dissolved oxygen, chlorophyll fluorescence and PAR should be collected twice daily from three sites (Hobsons Bay, central Bay, Werribee) using programmable buoyancy sensors.

The current EPA fixed site sampling program should be supplemented to include vertical profiling of the above variables at each site once per month. Underway analysis of salinity, temperature, chlorophyll fluorescence and nutrient (ammonium, nitrite, nitrate, phosphate, silicate) should be carried out monthly during the EPA fixed site sampling program to give a bay-wide snapshot of water quality. The timing of the EPA sampling could be varied to allow the impact on water quality of special events (eg. a large Yarra flood) to be mapped.

A pilot study should be carried out of the effectiveness of satellite monitoring of chlorophyll biomass and productivity.

**3. Monitoring macroalgal biomass and cover.** Quarterly surveys should be carried out of the cover and biomass of macroalgae at five fixed sites along the western and eastern coasts between Werribee and Frankston. Four depths per site should be sampled. At each depth, a 100 m video transect should be carried out along the isobath, along which 10 quadrats should be sampled for biomass and cover. Biomass is estimated from representative samples, and extrapolated on the basis of the video cover.

**4. Monitoring benthic macroinvertebrates.** Annual sampling of infauna and epifauna with a benthic grab or modified dredge is proposed at 22 sites throughout the bay. All macrobenthos collected will be identified to species level.

A pilot study is proposed, in which a range of exotic infauna will be established in laboratory tanks. Following a period sufficient to allow representative sediment

structure to be established, the impact of varying exotic species and biomass on sediment denitrification efficiency will be measured.

Indicative costs of each of the programs and pilot studies have been calculated.

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## APPENDIX 1. ESTIMATED COST OF MONITORING PROPOSALS

### 1. Denitrification efficiency cost estimates

These costs assume duplicate estimates of fluxes at one site over 24 hours. The number of sites to be sampled, and frequency of sampling, depends on the outcome of statistical analysis of existing data, though a minimum of three sites sampled twice per year has been indicated above. All costs include overheads. Costs are presented for two alternative methods of sampling (automated and manual chambers). Automated chambers can be deployed, operated and recovered without the need for divers, leading to considerable savings in salaries. However, they do not provide as many replicate measurements as an array of manual chambers. The first proposal is to use an existing automated chamber, and to construct a second automated chamber to provide replicate information from each site. Chemical analyses include the cost of salinity and dissolved oxygen calibration samples, and the analysis of seven samples per chamber for ammonium, nitrite, nitrate, phosphate, silicate, pH and alkalinity.

**Table 4a. Cost estimates for sampling benthic fluxes with automated chambers.**

Item	Cost per site (2 fluxes)
Up-front (construction of second chamber)	\$10,000
Boat (8 hrs), staff etc (2 x 8 hours).	\$1,490
Chemical analysis (14 samples)	\$1,560
Reporting/interpretation (0.5 day)	\$2250

Costs for any site after the first would be the same, less up-front costs (ie. \$3,275). Boat and staff costs would increase at a less than proportional rate with an increasing number of sites, since chamber recovery from one site and redeployment at the next site could be carried out on the same day for no extra cost. For example, deployment at two sites over three days would cost an extra \$1,035 in boat and staff costs. Shorter-term deployments would be possible in Hobsons Bay, leading to a halving of the boat and staff costs. A sequential sampling program, of deployment and recovery in Hobsons Bay, redeployment off Werribee (day 1), recovery and redeployment in the central Bay (day 2), and finally recovery (day 3) could be completed in three days, for an on-going cost of \$9,150, and an annual cost for two seasonal deployments of \$18,300.

An alternative approach may be to use an existing multi-chamber array. This is manually deployed by SCUBA, which allows the estimate of four replicate fluxes, but its use is limited (and expensive) in deep water because of OH&S considerations. For example, while the automated chamber provides seven samples from which to estimate fluxes, the manual chambers can only be sampled twice by SCUBA in one day at the central Bay depth. This leads to greater statistical uncertainty in flux estimates. At this depth, diving regulations require three divers on the vessel, so salary costs are greater than for automated chambers.

**Table 4b. Cost estimates for sampling benthic fluxes with manual chambers.**

<b>Item</b>	<b>Cost per site (4 fluxes)</b>
Up-front	-
Boat, SCUBA, etc.	\$4,050
Chemical analysis	\$3,120
Reporting/interpretation	\$450

**Table 4c. Cost estimates for sediment sampling as surrogate for estimating denitrification efficiency with benthic fluxes (assuming success of pilot study 2 in Table 4f below).**

Three sediment cores are collected from each site and sectioned into 12 intervals. Pore waters are extracted and analysed for nitrate or silicate concentrations.

<b>Item</b>	<b>Cost per site (3 cores, 12 depths)</b>
Up-front	
Boat, SCUBA, pore water extraction etc.	\$900
Chemical analysis	\$750
Reporting/interpretation	\$450

**Table 4d. Cost estimates for laboratory incubation of sediment for isotope pair (<sup>15</sup>N) estimation of denitrification.**

<b>Item</b>	<b>Cost per site (3 cores, 6 samples per core)</b>
Up-front (laboratory incubation system)	\$3,000
Boat, SCUBA, etc.	\$600
Chemical analysis	\$1,100
Isotope analysis	\$3,600
Reporting/interpretation	\$450

**Table 4e. Cost estimate for PILOT STUDY 1 (comparison of denitrification efficiency estimated from laboratory incubation of sediment cores and benthic chambers)**

A comprehensive comparison may require parallel sampling at three sites quarterly for two years. Duplicate chambers would be deployed at one site, from which seven samples each would be collected. Triplicate sediment cores would be collected from each site, returned to the laboratory and incubated. Six samples per core would be produced. Assumes item 4d does not proceed (duplication of some costs).

<b>Item</b>	<b>Cost per site (3 cores, 6 samples per core)</b>
Capital (laboratory incubation system)	\$3,000
Boat, SCUBA, etc.	\$2,670
Chemical analysis	\$2,005
Reporting/interpretation	\$450

**Table 4f. Cost estimate for PILOT STUDY 2 (surrogate estimate of denitrification from nitrate and silicate depth profiles).**

As in 4e, the same comparisons would be made between sediment cores and benthic chambers (two chambers, three sediment cores per site). However, in this case, the sediment cores would be sectioned into 10 intervals and pore waters analysed for nutrient content. No laboratory incubation would be required.

<b>Item</b>	<b>Cost per site</b>
Boat, SCUBA, etc.	\$2,670
Chemical analysis	\$2,005
Reporting/interpretation	\$450

## **2. Water column nutrient and chlorophyll stock monitoring cost estimates**

Costs are calculated on the assumption that an Ocean Sensors Autonomous Profiling Vehicle (APV 200) is deployed at each site. This unit is essentially an instrumented float whose buoyancy can be altered to make it rise and sink through the water column in a programmed fashion. Surface and bottom water column measurements can therefore be collected by the one unit. These measurements are necessary to allow us to measure stratification in the water column, which is critical to reductions in dissolved oxygen concentration. The precision and accuracy of the nominated sensors is adequate both for the detection of long-term change and for the detection of short-term changes in stratification. The sensors are the cheapest currently available in the one package from Australian agents, which have the required sensitivity and reliability. The system as costed would allow the later connection of PAR and fluorescent sensors, if they are not installed at the start. Sensor costs are based on an exchange ratio of US\$ 0.63 per A\$. Leasing has not been considered, since leasing of marine scientific equipment is usually arranged so that the full cost of the instrument is recovered within a year. Experience at MAFRI suggests the expected life of the sensors is 6-9 years; depreciation of 20% per year is included in the table below.

The sensors would be tethered to a bottom mooring, and could be recovered from the surface without the need for divers.

The sensors would need to be serviced at least every three months, when they would be cleaned, data down-loaded and sensors re-deployed. An alternative telemetry system would allow instantaneous verification of correct operation of the sensors, but also requires an above-water aerial. It will not add significantly to the ability to identify an early warning of increasing eutrophication, nor reduce the frequency of servicing.

The number of sites to be instrumented should relate to the number of fixed sites sampled (see below).

**Table 5a. Indicative costs of continuous sampling arrays, per site.**

<b>Item</b>	<b>Item</b>	<b>Cost</b>
<b>One-off Capital Required</b>	Salinity, temp, depth, DO	\$23,365
	1 x Fluorescence	\$6,921
	1 x PAR	\$1,905
<b>Depreciation</b>	20%/year	\$6,440
<b>Optional</b>	(Telemetry: mobile phone, interface, aerial)	\$4,000
<b>Annual servicing costs</b>	Servicing (boat, staff x 2)	\$1,600/day x 4 days=\$6,400
	Consumables	\$600
	Data processing	\$400

The sampling of fixed sites assumes one depth-integrated sample only is collected from each site, though physicochemical measurements (S, T, DO, PAR, fluorescence) would also be made throughout the water column. The assumption is made that any institution likely to be involved in the work would already have the required equipment, but that an operating cost would apply. Chemical analyses carried out include calibration samples for salinity and dissolved oxygen, and chlorophyll, ammonium, nitrite, nitrate, phosphate, silicate, dissolved organic and particulate N, P and C. The number of sites sampled should be governed by statistical analysis of spatial and temporal variability of water quality. High-performance liquid chromatographic (HPLC) analysis of photosynthetic pigments is proposed, to provide information on both broad taxonomic groups of plankton, and also to identify biomarkers for some species of interest.

**Table 5b. Indicative costs of fixed site sampling.**

<b>Item</b>	<b>Cost</b>
Sampling (boat, staff, equipment operating cost)	\$2,400
Chemical analysis	\$260
Data interpretation	\$400/site/year

Sampling costs could be shared between several sites (up to 6-10 could be sampled for the same cost).

The mapping cost is based on the operating cost of the MAFRI system, since this is the only one currently available in Victoria. It is assumed it is applied bay-wide over one day, though it could also be used in a small area of the Bay (eg. throughout and off Hobsons Bay) several times during an event (eg. high Yarra flow) to determine the rate at which nutrients are removed from the flood plume.

**Table 5c. Indicative costs of nutrient mapping (one event, mapped over one day).**

<b>Item</b>	<b>Cost</b>
Vessel and equipment set-up	\$730
Vessel operating (6 hours)	\$1,000
Salaries (2 EPA, 1 MAFRI staff, 10 hrs)	\$962
Equipment operating (1 day)	\$675
Calibration analyses (10 each chlorophyll, salinity, DO)	\$300
Data analysis and reporting (21 hrs)	\$1,014

CSIRO has the capacity to develop and test techniques to monitor chlorophyll, suspended solids, light attenuation (Kd), and coloured dissolved organic matter (CDOM) in optically deep waters in Port Phillip Bay using current and planned ocean colour satellites. This currently excludes the near-shore areas shallower than about 10 m.

The cost of generating algorithms to convert SeaWiFs satellite data to chlorophyll *a* estimates for Port Phillip Bay are included in Table 5d (Pilot Study 3). These costs assume that:

- light attenuation data will be gathered by the automated sampling system;
- NASA will provide the images for free;
- Samples for other local measurements (coloured dissolved organic matter [CDOM] concentration) can be collected by EPA for no extra field cost.

The outputs include:

- Seasonal in situ bio-optical data set for Port Phillip Bay.
- Remotely sensed coastal water quality products (chlorophyll, CDOM, SS, Kd) for Port Phillip Bay.
- Assessment of satellite product accuracy and precision against EPA data set.

**Table 5d. Indicative cost of PILOT STUDY 3 (estimating chlorophyll a concentration from SeaWiFs satellite).**

Item	Cost
Salaries	\$46,502
Operating	\$ 4,000
Travel	\$ 8,200
CSIRO on-costs	\$17,312
<b>TOTAL</b>	<b>\$76,312</b>

### 3. Macroalgal biomass monitoring cost estimates

Assumes all sites can be sampled over two days (video for cover, diver for biomass). Three people in the field. 4 depths per site. 100 m video transect per depth. 10 quadrat samples collected per transect. Number of sites and frequency should be governed by statistical analysis of existing data.

**Table 6a. Indicative costs of monitoring macroalgal biomass and cover.**

Item	Cost per site
Field work (sampling, video)	\$2,400
Sorting, biomass, video interpretation	\$600
Reporting 0.5 day	\$225

Two-three sites could be sampled for the same field costs.

### 4. Monitoring benthic infauna.

Based on collection of 22 grabs per year; monitored annually. Sorted to identify all species (to detect future introduced species). Biomass estimated for each species.

**Table 7a. Indicative cost of monitoring benthic infauna.**

Item	Cost	Number	Annual Cost
Consumables	\$500	1	\$ 500
Sampling	\$3,200/day	3	\$ 9,000
Sorting, ID, biomass	\$1,000/sample	22	\$22,000
Reporting	\$400/day	15 days	\$ 6,000
<b>Total</b>			<b>\$45,500</b>

**Table 7b. Indicative cost of PILOT STUDY 4 (measuring the impact of exotic fauna on denitrification efficiency).**

Assumes laboratory tanks are set up with representative native infauna in a sediment layer. Varying numbers of exotic fauna (*Sabella* and *Corbula*) would be introduced to chambers in the tanks, and changes in fluxes measured relative to chambers without exotics. Assumes two chambers at each of 5 levels of biomass, by two species, plus four controls (24 benthic chamber incubations).

Item	Cost
Sample collection	\$1,500
Establishing and maintaining tanks	\$2,000
Measuring benthic fluxes	\$1,200
Chemical analysis (\$830 x 24)	\$19,920
Reporting	\$2,400

**TOTAL COST**

If all of the programs were implemented at the recommended number of sites and frequencies, a one-off capital cost of \$106,600 and annual costs of \$159,780 would be required. The pilot studies, if run as recommended, would cost \$178,200 in the first year, and \$121,200 in the second year.

## APPENDIX 2. WORKSHOP PARTICIPANTS

<b>Participant</b>	<b>Involvement/Organisation</b>
Rod Gowans	Director, Parks, Flora and Fauna, NRE
John Beardall	PPBES contractor, Monash University
Fiona Bird	PPBES contractor, LaTrobe University
Stuart Campbell	EPA Marine Science
Scott Chidgey	PPBES contractor, CEE
Don Hough	PPB environmental management plan, NRE
Phill Johnstone	EPA Water and Catchment Policy
Joanne Klemke	PPB environmental management plan, NRE
Brett Light	PPBES contractor, EPA
Andy Longmore	PPBES contractor, MAFRI
Nancy Millis	PPBES Scientific Review Committee
Brian Newell	PPBES Project Manager
Geoff Nicholson	PPBES contractor, MAFRI
John Parslow	PPBES Technical Group
Simon Roberts	PPBES contractor, Monash University
Andy Steven	EPA Marine Science
Geoff Westcott	Victorian Coastal Council Scientific Panel

## **APPENDIX 3. NOTES FROM WORKSHOP: REDUCING RISKS ASSOCIATED WITH WITHIN BAY NUTRIENT CYCLING: MONITORING AND CRITICAL SCIENTIFIC UNCERTAINTIES**

### **1. CONTEXT<sup>1</sup>**

The purpose of the 19 October 1998 workshop was to provide scientific advice on the monitoring approach, indicators and key research questions that, according to current scientific understanding of Bay nutrient cycling, should be priority components of a proposal to address the following objective:

*“To provide an early warning of detrimental changes to critical elements of Bay nitrogen cycling processes that indicate an increased risk of eutrophication at Bay-wide and regional scales.”*

The four planned workshop outputs were:

- a) Advice on the objective and its expression from a scientific perspective.
- b) Advice on priority monitoring approaches and indicators to address the above objective.
- c) Advice, from a nutrient cycling perspective, to guide the next step of designing a monitoring proposal and interpretation approach for priority indicator/s.
- d) Advice on remaining gaps in understanding of Bay nutrient cycling that are critical to future refinement of nutrient management strategies.

### **2. SYNTHESIS WORKSHOP DISCUSSION**

#### **2.1 Output (a)**

No concerns were raised in terms of scientific feasibility or expression of the objective.

#### **2.2 Outputs (b) and (c)**

These outputs were largely addressed together, focussing on (b). Of key relevance to output (c) is the specific amount of change in, or levels of, the recommended indicators that should signal concern, and over what duration. The likelihood that various sampling scenarios would provide data allowing detection of such changes will be an important consideration in the design of a monitoring program. Participants advised that a review of existing Bay-study data would be required to determine critical levels / duration of change, and this would be best addressed as a subsequent step to the workshop.

Although there are gaps in relevant scientific understanding (see Section 2.3), understanding of Bay nutrient cycling processes was considered sufficient to develop a monitoring program

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<sup>1</sup> For the discussion paper that was circulated prior to the workshop, see NRE file NP/01/0018.

### 2.2.1 Sediment fluxes

High priority monitoring component in conjunction with water quality monitoring

#### Approach

Monitor indicators of sediment nitrification / denitrification processes. Use benthic chambers to measure fluxes of key parameters between sediments and water column at a few critical fixed locations. Surrogate monitoring approaches that are cheaper and logistically simpler would need to be identified to make more detailed monitoring of the spatial extent of reduced denitrification efficiency realistically feasible

#### Indicators

Fluxes of C, N, Si, P, O between sediments and the water column, denitrification, decomposition and irrigation rates (from Bay Study Final Report – p 220)

#### Signal of Concern & Confidence in Interpretation

Trends in the above indicators over time (may be through consideration of indicative patterns rather than quantitative demonstration or interpretation); Change in the spatial extent of lower denitrification efficiency (but note identification of surrogate measurements needed for spatially intensive monitoring)

*Andy Longmore has since suggested that the 4 flux replicates / site used previously could be spread over 4 separate sites at similar cost –relative merits would be influenced by relative statistical power of data analyses for the 2 approaches (which would be influenced by what statistical approach is used) vs potential surrogates also*

*John Parslow has since said that it is questionable whether we have adequate time series or understanding to interpret temporal changes in sediment fluxes (eg: monthly monitoring off Werribee ( only site where monthly measurements were made in PPBES; 6 monthly elsewhere) showed strong shifts in denitrification efficiency that are not well understood. If monitored infrequently (say 6 monthly), a drop in efficiency would be difficult to interpret (in terms of whether it represented a long term shift in Bay function or a small, local or short-lived phenomenon). Therefore would not necessarily provide an early warning as may take several years before it was clear that denitrification efficiency had significantly diminished. May be possible to design a more adaptive program, where an observed drop in denitrification efficiency would trigger more intensive sampling but, given expense of flux measurements, would not initiate an intensive program lightly => important to develop cheaper surrogate measurements / indicators of denitrification efficiency.*

#### Early Warning?

Not discussed explicitly; our interpretation of the general discussion is that this would provide a relatively early warning of breakdown of denitrification efficiency at monitored sites, but that only limited spatial coverage is feasible using current approaches and technology.

*Andy Longmore has since suggested that, although appropriate timeframes for measurement have not yet been discussed, he suspects an early warning would be possible on no shorter than a seasonal timeframe.*

#### Scale

Not discussed explicitly, our interpretation is relevant Bay-wide and to monitored regions

#### Sites

Several options were discussed – we did not identify a specific recommendation although the third option seemed to receive emphasis and was not opposed

- Continue monitoring of particularly the PPBES sites at Hobsons Bay, Werribee and in the Bay centre (detailed locations not discussed). The scope of the discussion did not include locations for additional sites should sufficient funding be available and

other components of the approach suggested in the Bay Study Final Report (a site at Corio Bay and a transect from Centre to Hobsons Bay) were not an emphasis of discussion (but see dot pt below re Hobsons Bay). Development of surrogate indicators to provide for more detailed spatial mapping was considered important

- Relocate PPBES Hobsons Bay site, or add another site, at the edge or beyond area of currently low denitrification efficiency. This would provide some indication of changes in the extent of this area as opposed to changes in efficiency within it. Spatial mapping particularly in the Hobsons Bay area may first be required to better define this area
- Use some / all water column monitoring sites (see Section 2.2.2) to improve coordination between monitoring components and resulting data

*John Parslow has since suggested that continuation of monitoring at PPBES Hobsons Bay site may depend on context & objectives; if expect ↓ in Yarra load, might monitor in Hobsons Bay to detect ↑ in denitrification efficiency BUT if looking for early warning of denitrification, could check for expansion of zone of low denitrification efficiency (there was discussion at workshop about a transect from Hobsons Bay to Bay centre provided a suitable surrogate could be identified; continuation of PPBES sites in Hobsons Bay & Bay Centre would anchor the ends of the transect); As for other potential monitoring components, need an assessment of (a) likely cost of flux measurements & affordable # sites & sampling frequency; (b) spatial & temporal variability, sampling needed to detect significant change (difficulty is that these measurements are very expensive & it may not be possible to fund routine sampling schemes which are statistically adequate).*

### 2.2.2 Water Column

Continuous and regularly sampled fixed sites are high priority components; spatial mapping is of lower priority

#### Approach

- Continuous monitoring at fixed sites to provide detailed temporal information (*Scott Chidgey thought that in the long term this may be reduced to more manageable statistics & periodic sampling*)
- Regular sampling at fixed sites to provide additional parameters and better spatial coverage (depending on number of continuous meters) at coarser temporal resolution
- Detailed spatial (transects) mapping (if achievable at low cost) at targeted locations

*Subsequent input from John Parslow – satellite remote sensing from current & planned ocean colour sensors is a potentially low cost means to monitor chlorophyll & turbidity in Bay waters with horizontal resolution of 300m – 1km on time scales of days (see further information on these in JP's input on research needs; would require modification of standard algorithms (CSIRO does this type of work); proposed routine water quality measurements would provide an ideal basis for validating the algorithms)*

#### Indicators

**Continuous:** dissolved oxygen, salinity, temperature, chlorophyll fluorescence, PAR over depth (from Bay Study Technical Report 43)

**Regular:** standard suite of nutrients (Note: these are nitrate; nitrite; ammonia; phosphate; silicate; particulate C, N and P; dissolved organic C, N and P), chlorophyll, light attenuation (PAR). Phytoplankton composition including toxic species is not a critical priority for this monitoring objective; include if can be done easily and cheaply

**Mapped:** salinity, temperature, dissolved oxygen, chlorophyll fluorescence, standard suite of nutrients (from Bay Study technical report 43)

*Subsequent input from John Parslow – suggest include turbidity (& light attenuation – PAR already included above for 'continuous' & 'regular') as indicators due to their importance to benthic plants including seagrass &*

*microphytobenthos*

### Signal of Concern & Confidence in Interpretation

Decrease in bottom water dissolved oxygen, increase in DIN and chlorophyll [Scott Chidgey since suggested organic N but with a question mark]. Note that whilst bottom water DO levels are predicted by modelling to decrease with deterioration of denitrification, this is not strongly supported by Hobsons Bay data - subsequent input from John Parslow - his understanding is that DO levels in bottom waters in Hobsons Bay have historically been lower than those elsewhere, reflecting high benthic respiration rates there; however, significant DO depletion will only occur under prolonged stratified conditions which may be infrequent

*John Parslow since suggested adding increases in turbidity and decreases in light attenuation*

### Early Warning?

Not discussed explicitly; potential for greater spatial and temporal resolution than sediment flux.

*Note there was also some discussion at the workshop about targeting some of this sampling deliberately at flood events, but no clear position was reached (the workshop did not get to temporal sampling patterns and frequency). Subsequent input from Scott Chidgey – suggested that continuous monitoring (eg: event triggered) may be the best way to monitor such short term events.*

*Subsequent input from Andy Longmore - the important time scale for DO drop may be days rather than weeks (fortnightly measurements have not recorded low DO associated with low denitrification efficiency in Hobsons Bay as predicted by the model)*

*Geoff Nicholson since pointed out that, although loggers can collect very frequent data, earliness of warning is limited by frequency of data downloading (unless telemetry etc involved)*

*Subsequent input from John Parslow – use of the PPBES integrated model (+ input of observed forcing data & loads) as a tool for interpreting & extending results of water column & other monitoring data; allows potential to: (a) interpolate between fixed sites (provided agreement between model & observations remains good); (b) interpret observed changes as due to changes in physical forcing, load or internal processes; (c) identify & investigate changes in system behaviour which result in divergence between model predictions & observations – could provide early warning of shifts in Bay function (although – my comments – presumably such divergence could be because the model imperfectly represents system function OR system function has changed – would require investigation)*

### Scale

Not discussed explicitly; our interpretation is that is relevant Bay-wide and to monitored regions

### Sites

**Continuous & Regular:** Current EPA fixed sites (ie: Central, Hobsons, Long Reef, Corio) with recommended additions of an eastern Bay site (previous EPA Patterson River site was suggested;

*Andy Longmore since suggested that the PPBES Sandringham site may be a better choice as sampling was longer & more regular than the EPA Patterson River site & was carried out for the recommended suite of measurements) and a site at the Heads*

**Mapped:** along transects through the fixed sites / in areas of gradients / hotspots / activities relevant to nutrient cycling (consideration of cost is next step)

*Scott Chidgey has since suggested temporal frequency of fortnightly to monthly but rationale not provided*

### **2.2.3 Benthic Macroalgae**

Lower priority than components outlined in Sections 2.2.1 and 2.2.2 although may be important for their interpretation; as this is relevant to other Bay management

objectives, there may be potential for integration with other programs

### Approach

Survey cover (potentially by video) and / or biomass in relevant parts of the Bay

### Indicators

Biomass and cover of unattached algal assemblages west of the Yarra (although the attached benthic algal assemblages more common east of the Yarra were also mentioned, they did not seem to be the key target – this was not clearly resolved)

### Signal of Concern & Confidence in Interpretation

Change in cover – research may be required to allow confident interpretation of patterns

*Subsequent input from John Parslow – resolving spatial & temporal variation & interpreting changes will be the key issue; need to be able to clearly & quantitatively state the level of change deemed significance (then statistical analysis needed to identify sampling design required to detect this change).*

### Early Warning?

The focus would be on detection of longer-term responses than components outlined in Sections 2.2.1 and 2.2.2.

### Scale

Relevant Bay regions (Bay study surveys found particularly abundant macroalgae on the north-west side of the Bay)

### Sites:

Specific locations not discussed

*Scott Chidgey has since suggested “representative sites” on west side of Bay and controls on east side [Andy Longmore & Jo Klemke - these east & west side areas are probably better considered as areas potentially subject to different impacts; CSIRO modelling predicts that the east side is more affected by inputs from the Yarra and Patterson / Mordialloc (some areas), while the western side is more affected by the WTP plume – see report 46] . Scott suggested frequency of quarterly for first 2 years, then annually in critical season.*

*See also input from various workshop participants on role of macroalgae in Bay N cycling as a knowledge gap (this provides insights on degree of uncertainty in this area)*

## 2.2.4 Benthic Macroinvertebrates

Lower priority than components (i) and (ii) although may be important for their interpretation<sup>2</sup>; as this is relevant to other Bay management objectives, there may be potential for integration with other programs

### Approach

This was not discussed in detail but would presumably be benthic surveys

### Indicators

Composition of benthic macroinvertebrate assemblages at a taxonomic resolution of at least functional groups, major bioturbators and bio-irrigators

*Scott Chidgey has since also suggested volumes (need clarification on this)*

### Signal of Concern & Confidence in Interpretation

Shift from current composition in terms of functional groups; detection of exotic species – research may be required to allow confident interpretation of patterns

*Subsequent input from John Parslow – resolving spatial & temporal variation & interpreting changes will be the key issue; need to be able to clearly & quantitatively state the level of change deemed significance (then statistical analysis needed to identify sampling design is needed to detect this change).*

### Early Warning?

The focus would be on detection of longer term responses than components outlined in Sections 2.2.1 and 2.2.2, although it was mentioned that important changes to macrobenthic invertebrates that have a significant role in sediment nutrient cycling processes (through bioturbation / bioirrigation etc) may provide a warning of potential impending changes in nitrification / denitrification efficiency

### Scale

Bay-wide

### Sites

No specific sites were identified but a bay-wide sampling regime was intimated

## 2.3 Output (d)

Output (d) was “advice on remaining gaps in understanding of Bay nutrient cycling that are *critical* to future refinement of nutrient management strategies”.

Consolidated advice on this output was sought from participants following the workshop.

### *Management Context for Output (d)*

The subject of the workshop was: development of a proposal for monitoring and targeted research “to provide an early warning of detrimental changes to critical

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<sup>2</sup> See list of remaining uncertainties raised at the workshop – Section 2.3

elements of Bay nitrogen cycling processes that indicate an increased risk of eutrophication at Bay-wide and regional scales”.

Other current and planned focuses for refinement of Bay nutrient management approaches include:

- Management of Bay activities that may detrimentally affect nutrient cycling at Bay-wide, regional or local scales
- Management of risks to localities and regions of the Bay arising from catchment inputs
- Setting of future long-term targets for managing external loadings
- Setting of future environmental indicators and criteria relevant to nutrient cycling processes.

For Output (d) it was intended to identify a short list of *key* gaps in the scientific understanding of nutrient cycling needed to advise the development or refinement of the above management approaches. The main focus was gaps that are both *critical* and can realistically be advanced over the coming decade. However, it was also recognised that it would be useful to separately identify important directions for longer-term strategic research generally relevant to Bay nutrient management. Participants were there asked:

- to identify a short list of key priorities, reflecting their consideration of both the suggestions that arose during the workshop (Box 1) and their further views in the context of the above management directions, and
- that with each proposed critical knowledge gap be accompanied by a dot-point supporting rationale including at least the following information:
- Research Question
- Short-term or strategic priority  
High / Medium / Low Priority
- How will it advise management?
- Are further research steps needed before it advises management?

The results of this process are held in internal NRE files, see NP/15/0021.

## Box 1. Knowledge gaps identified during the workshop

The following knowledge gaps were suggested during discussions about outputs (b) and (c). They are not in any particular order.

- Identification of surrogates for measurements of sediment fluxes from benthic chambers:
  - Is there scope to identify options from further assessment of existing data eg., interstitial “squeezates”?
  - Is there a general relationship between the depth or volume over which nitrification / denitrification occurs and denitrification efficiency? Could such parameters be used as surrogate measurements?
- Identification of the specific critical amount of change in, or levels of, the recommended monitoring indicators (see Appendix 2) that should signal concern, and over what duration.
- Better understanding of what controls sediment denitrification processes
  - Why is denitrification efficiency so high in the Bay centre? Could MPBs in centre be producing small molecules that provide a carbon source for denitrification?
  - Where in the sediments does denitrification occur?
  - Is the lower denitrification efficiency in Hobsons Bay indicative of a phenomenon spreading in area across the Bay or is it localised and not changing?
- Identification of factors other than input loads that could lead to breakdown of denitrification
  - How do particular benthic faunal species or functional groups, including exotic species, and more general changes in the composition of benthic assemblages affect denitrification (sediment / water fluxes)?
  - What is the role of sediment disruption – eg., are dredging and stirring responsible for the reduced denitrification efficiency in Hobsons Bay?
- Better use of targeted monitoring of large scale perturbations to build understanding at relevant scales – eg., what effect has cessation of scallop dredging had on sediment fluxes?; how does the Bay respond to large scale flood events
- Better understanding of the role of macroalgae in Bay nitrogen cycling
  - How do macroalgae affect sediment fluxes and denitrification?
- Better understanding of the role and importance of seagrass beds to nutrient fluxes, and potential for their use as indicators of relevant aspects of Bay water quality
- Better knowledge of aspects of the understanding underlying the Bay nutrient cycling model that required significant and probably influential assumptions:
  - How accurate are the estimates of P and N burial within Bay sediments?
  - To what extent is respiration limited by oxygen exchange and does the model deal with this?
- Better understanding of which areas of the Bay to focus on in terms of “the science” – ie., monitoring and / or building scientific understanding
  - This was not extensively discussed but Hobsons Bay, the Heads & Werribee arose.